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EMISSION DENSITY ZONING

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Emission density zoning is an air quality control strategy whereby all parcels of land within an air quality maintenance area, excluding public rights of way and reserved open space, are assigned maximum legal emission allowances for particulate matter and sulfur oxides, expressed in terms of mass of pollutant per time period per lot area. The subject of this publication is the development of criteria for (a) partitioning an air quality maintenance area into component areas, (b) the setting of emission density limits for all land uses in each component area and, separately, all major emission sources, and (c) the revision of the emission density limits as conditions change. The criteria are then translated into a generalizable decision model, a linear program, for setting the emission density limits. The criteria and model are tested in two air quality maintenance areas, Baltimore and Louisville.

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SECTION 1

INTRODUCTION AND SUMMARY

INTRODUCTION

Emission density zoning is an air quality control regulation whereby a maximum legal rate of air pollutant emissions is prescribed for certain parcels of land. The limits are expressed in terms of mass of pollutant per time period per lot area. The maximum legal rate, or emission density limit, would vary with the location and the planned use of the land parcel.

The concept of an emission density strategy is not new. An early discussion of its potential was published by the National Air Pollution Control Administration in 1968.[29] Subsequently, John Roberts and Edward Croke of Argonne National Laboratory contributed greatly to a definition of an EDZ control strategy, its potential, and its limitations.[30,31] Emission density related control strategies, similar but not the same as those contemplated in this report, have been implemented in Chicago, Illinois and Louisville, Kentucky.[26,32]

In concept, it is very similar to the typical use of density and bulk regulations in land use zoning. Each parcel of land is assigned a permitted use; e.g., residential, commercial, and the permitted uses have associated maximum densities. For example, a residential zone may have a maximum density of two dwellings per acre; i.e., a minimum lot size of 1/2 acre. Similar restrictions are placed on commercial and office zones, frequently in terms of a floor area ratio (FAR), which specified the maximum amount of building floor area per lot area. For example, a four-story building covering one-half of the lot would have a FAR of two.

Land-use zoning is usually applied to all areas of the city, both developed and undeveloped. Developed; i.e., currently built on, land can expand or redevelop up to the maximum permitted density and use for its zoning class. One land use may have differing maximum permitted densities in various areas of the city; e.g., for residences, one may find areas zoned for a minimum lot size of 2 acres and other areas in the same city zoned for 1/2-acre lots. Emission density zoning could also be implemented in this manner, such that all areas of the region are controlled and that similar land uses have different maximum emission densities, depending on their location within the city.

This report describes the criteria for setting the emission density limits in a metropolitan region, a model for setting the limits, and examples of the application of the criteria and model. The region considered is an air quality maintenance area[1] because this is convenient for air quality planning purposes (though other regions could be employed). The model sets emission density limits for a grid network of squares called component areas. It is assumed that either all the land use within a particular category in a component area will have identical emission density limits, or that a local jurisdiction will reassign emission density limits reflecting local planning goals but not increasing the total permitted emissions within the component area.

In a manner similar to land-use zoning, the emission density zoning model described in this report is based on a land use plan. It adopts the amount and configuration of land use for a specified future date, called a design year, and sets a pattern of emission density limits that achieve an adopted objective. The emission density limits are sufficiently high on every parcel of land to permit development as contemplated in the land use plan. However, in some areas they would be so stringent as to permit only certain types of the broad category of development outlined in the land-use plan, to require the application of emission control techniques, or to require development of a lesser density; i.e., the same kind of development on a larger parcel of land. In other areas, the potential development will not be so restricted.

This dependence on a region's land-use plan, as well as specific implementation concerns, requires the substantial involvement of city and regional planners as well as air pollution control engineers in the setting of emission density limits and the implementation of an emission density zoning ordinance.

It is possible (and, in fact, may be desirable) that emission density zoning be implemented with the provision for transferable emission rights. This would be similar to transferable development rights in conventional zoning. A market for transferable emission rights is attractive in that it will allow the pattern of set emission limits to change with changes in growth patterns, yet still maintain the National Ambient Air Quality Standards (NAAQSs). Transferable emission rights may be necessary to ensure the legal and political acceptability of emission density zoning. The Environmental Protection Agency's proposed Emission Offset policy (41 FR 55524 and 55558) almost certainly will stimulate development of such a market. The required new institutional mechanisms, however, are not considered in this report.

Emission density zoning, as contemplated in this report, would include the following procedures:

- Each compartment area and, separately, each major stationary source, will be assigned emission density limits by the regional authority that are the maximum densities of annual* emissions of sulfur oxides (SO_x) and particulate matter (PM).

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*Annual emission density limits, to be effectively enforced, probably will require translation into daily limits.

- Except for major stationary sources, all land of the same land use category in a component area, as specified in land use plans and/or zoning ordinances, will be assigned the same emission density.

- Every parcel of land in the region, excluding public rights-of-way and reserved open space, will have a fixed emission density limit.

- Local jurisdictions may reallocate but not increase emission limits within a component area as local plans, zoning, or planning goals change. Local jurisdictions may reallocate emissions among component areas under their authority subject to the constraints discussed in Section IV of this report.

- A market for transferable emission rights among industrial, and perhaps commercial, sources may be instituted according to the procedures described in Section IV of this report.

- Variances may be granted by a regional authority subject to the limitations described in Sections III and IV.

Brail[26] has defined four types of emission quota strategies, viz.

- Emission Allocation Planning - (jurisdictional emission quotas) under which the air pollution control agency allocates permissible emission quotas by local government jurisdiction within its region. No attempt is made directly to apply the emission quota to new stationary sources.

- Floating Zone Emission Quotas - in which a limitation on pollutants generated within an area of a specified size which can be drawn about any specific location within the metropolitan area.

- District Emission Quotas, a step down from emission allocation planning, a strategy which limits the amount of pollutants to be emitted during some time period from a planning district within a jurisdiction.

- Emission Density Zoning in which the emissions of a pollutant be limited to prescribed levels for a selected unit area.

The subject of this report does not fit neatly into any of the above categories. The output of the decision model does provide unique emission density limits for every major point source; thus it may be called emission density zoning. It also provides emission density limits for every area source. The area source emission density limits are uniform for all land use of a particular category within a component area; i.e., grid square. Thus, the emission density limits for a specific land use within a component area can be summarized as an emission quota for that land use, an approach similar to district emission quotas. Moreover, in the contemplated implementation scenario, the total emissions in a municipality are treated as a jurisdictional emission quota which the municipality would be free (and encouraged) to reassign. Thus the subject of this report is a decision model for setting emission density limits, the contemplated implementation of which may include elements of emission allocation planning and possibly district emission quotas. If desired, the model can be used as a means of setting jurisdictional emission quotas or district emission quotas without assigning emission density limits.

ORGANIZATION OF THE REPORT

The remainder of this section is devoted to a summary of the report. The following three sections of this report describe the criteria for partioning a region into component areas, setting emission density limits, and revising the emission density limits at a later date as conditions change. Next, Section V describes the specification of a mathematical model, a linear program, for setting the emission density limits. Section VI describes a step-by-step procedure for executing the model. Sections VII and VIII illustrate the application of the criteria and model in two example regions, Baltimore and Louisville.

There are several appendixes. The first is a brief introduction to linear programming and should be read first by the reader unfamiliar with the technique. The second and third discuss two refinements of the model, the consideration of short-term air quality standards and the consideration of a functional relationship between sulfur oxide and particulate matter emission rates. Appendix D discusses the estimation of control costs for future emission sources, which is necessary for an alternate formulation of the emission limit setting model. Appendix E discusses the application of the model if attainment is a problem (i.e., air quality standards are currently being violated).

SUMMARY OF PROJECT

Criteria for partioning a region into component areas for the purposes of setting emission density limits were developed. This partioning of a region very closely approximates the process of gridding an air quality control region (AQCR) for the purposes of dispersion modeling. More attention, however, is given to minimizing the number of large grids spanning jurisdictional boundaries.

Criteria for setting emission density limits in component areas were developed and translated into a generalized mathematical model. The model was tested in two air quality maintenance areas (AQMAs), Baltimore, Maryland and Louisville, Kentucky. Criteria were also developed for revising the emission density limits due to unforeseen growth or changes in community land use plans.

The model for setting emission density limits is in the form of a linear program. The simplest formulation of the model is one that maximizes the aggregate regional emissions of air pollutants subject to the constraints that the NAAQSs are not violated and the emission density limit set for each source be in a feasible range. The maximization of emissions is assumed to be loosely associated with minimizing the conflict between maintaining the NAAQSs and regional economic growth. The opportunities for other formulations of the model are presented; among them is the minimization of control costs of firms complying with emission density limits.

The model for setting emission density limits (EDLs) is based on and assumes the validity of the land use element of the comprehensive plan for the region. The emission density zoning (EDZ) model does not alter the location of development within the broad categories of the plan. The emission density limits set by the model do place additional constraints on the nature of development at any one location. Within a broad category of development; e.g., light industry, the pattern of emission density limits identifies those locations in the region planned for such development that can more easily accommodate development with high emission rates and those areas that are more suited for low emission rates. In other words, the model identifies the optimal pattern of "carrying capacities" that maximizes the total emissions in the region (while maintaining the NAAQSs).

FINDINGS AND LIMITATIONS

The emissions maximization formulation of the model was tested in two AQMAs. In each AQMA it was executed twice, once for particulate matter and once for sulfur oxides, the two pollutants that are principally from stationary sources. (Pollutants such as carbon monoxide, which is generated primarily by mobile sources; e.g., the automobile, are not well-suited to control by emission density zoning.) Overall, the testing of the model was successful.

The model, however, assumes attainment of the NAAQSs; i.e., the air quality in the region is currently below the standards. If this is not the case, control strategies must first be developed to restrict the emissions of existing sources so that attainment of the NAAQSs is achieved. Moreover, the model assumes that if the region develops according to the land use plan and all future development employs the best available emission control technology while building facilities at the lowest development density economically feasible, the NAAQSs can still be maintained. The model operates, then, on the middle ground between the extremes of future development without additional controls (which is assumed to violate the NAAQSs) and requiring all future development to adopt the most stringent controls (which is assumed not to violate the NAAQSs). The model can be revised to accommodate situations outside this range.

Several problems may confront a user of the model. First, the size and complexity of the linear program increases rapidly with the number of emission sources; i.e., component areas. For metropolitan areas roughly the size of Baltimore or larger, the computer resources required to solve the linear program can become quite large; i.e., over an hour of computer time. In such cases it is possible to solve a series of smaller problems. One can solve the problem for a sample; e.g., 10 percent, of the receptors (locations at which air quality is calculated), and then use the solution to that problem as a starting point to solve the linear program with a full complement of receptors (or a dense field of receptors near those receptors projected to approach the NAAQSs).

Second, the user of the model must be able to specify the maximum emission density that can be expected in each land use category as well as the minimum emission density that is economically feasible and still compatible with development according to the land use plan. This is a critical data item; one can expect to devote a significant amount of manpower (several man-months) to compiling it. Many emission density limits will be set at one of these limits.

Third, the general pattern of emission density limits that can be expected implies that the land use plan must have addressed urban sprawl. In the model tests that were conducted, emission sources on the periphery of the region were set at their upper limits and sources at the center of the region were set at their lower limits. This pattern means that:

- Capacity expansion of existing sources at the periphery is favored over those in the center of the region. Centrally located sources cannot expand their capacity, and hence increase emissions, without reducing their emissions from current activities. Suburban sources are not so limited.

- The permitted emission densities on undeveloped land, within a specified category, are higher on the periphery of the region and lower in the center. This would seem to encourage development away from the center of the region unless there are more overwhelming locational advantages at the central location.

While such a pattern of emission density limits does not affect the amount of land planned for specific uses, it confers on peripheral locations a decided advantage. The congruence of this phenomena with other planning goals must be examined. A more balanced allocation of emission limits may be desirable, facilitating additional development at central locations at the expense of a lesser aggregate amount of permitted emissions in the region. It is this attempt at balance that the control cost and land value formulations of the decision model address.

Implementation Considerations

There are several considerations that will be faced by an agency implementing EDZ. One should first note that EDZ cannot be used to control natural and transported particulate matter, and emissions from nontraditional sources. Background pollution, auto exhaust, reentrained road dust, fugitive dust from construction, demolition, and quarrying and dust from unpaved areas and other urban activities fall into this difficult-to-control category. The contribution of background and nontraditional sources to each receptor must be projected for the design year. If the EDLs are met by every controlled source, it is still possible to violate the NAAQSs if the noncontrolled EDZ sources actual emissions are greater than was projected.

Implemention of EDZ will require substantial intergovernmental cooperation. A close working relationship between the staffs of the regional air pollution control agency and the regional planning agency is necessary — more so than in other aspects of air quality maintenance planning. Moreover, EDZ must be integrated into the regional planning process and must influence the transportation plan, water resource management plan, and land use element of the regional plan. The EDZ limit setting model computes an "optimal" set of EDLs without considering their effect on mobile source pollutants, water pollution, housing quality, core area revitalization, conversion of agricultural land, and other regional goals. This means that the regional plan must have already dealt with these issues. The EDZ model will then optimize the potential emission density pattern within the limits of the regional plan. The 208 and transportation plans must be based on, and be compatible with the regional plan.

Cooperation among and within regional agencies is not all that is required. EDZ also requires the involvement and commitment of local governmental units. Ideally, the municipalities in the region will internally reallocate the regionally-specified EDLs so that they will reflect local planning goals, and will include the implicit municipal emission quota as a constraint in subsequent revisions of the local land use plan. At a minimum, the municipality must include compliance with the EDL as an additional criterion when issuing building and occupancy permits. For example, the EDZ ordinance might require a certificate signed by a professional engineer stating an estimated average daily emission rate to accompany all permit applications. The municipality could then check compliance with the maximum permitted emission density as it now does for compliance with the maximum permitted development density. If the municipality is unwilling to cooperate in administering EDZ, a scenario like the one postulated earlier may be unfeasible. An unexamined issue is how one might require or force a municipality to administer EDZ.

If municipality-based administration of EDZ is unfeasible, a regional or state agency will have to administer it. This is less desirable, because it is likely that only sources above a certain threshold size could be checked for compliance. This limits the effectiveness of EDZ. A possible loss of flexibility in a regionally-administered system, and a possible lack of integration with local planning, also appear to make a regional system less desirable.

Another issue is how to ensure compliance with the EDL once a facility is operating. Most of the physical changes in a facility that would alter its emission rates can be controlled through the building permit process. There are, however, at least two other actions that alter emission densities and may be more difficult to control. An industrial facility may desire to increase its hours of operation. It may then not be in compliance with its EDL. More traditional emission control for point sources, administered by the regional agency, are thus still necessary in conjunction with EDZ. Also, a facility may change its land holdings, thereby changing its emission density. Some mechanism must be designed either to prevent a source from selling vacant land used only to satisfy EDZ, or to reduce the EDL on the land that was transferred to a new owner. A transferable emission rights market may alleviate this problem.

The legal basis for emission density zoning is unclear. While there appear to be no substantial issues raised if emission density zoning is implemented as a maintenance strategy,[26] a specific implementation strategy has not been reviewed. For example, because emission density zoning is patterned after land use zoning, should emission density limits for the same land use category in a component area differ among parcels? In conventional zoning, the regulations must be uniform for each class and kind of building within a district.

Finally, the political considerations inherent in assigning emission density limits should be noted. First, as previously mentioned, the issue of balance between the center city of a region and suburban locations must be addressed by the implementing agency. Second, the assignment of emission densities to component areas and, hence, the allocation of emissions to local jurisdictions constrains the zoning prerogative of the jurisdiction. Though the local jurisdiction may be permitted to reallocate emission rights among districts within its boundaries, the total emissions permitted from within a grid cell is essentially fixed. Third, emission density zoning, by assigning limits according to a regional land use plan, can become a substantial tool for implementing the plan.

SECTION II

CRITERIA FOR PARTITIONING AQMAs

INTRODUCTION

Emission density zoning (EDZ) requires the partitioning of an air quality maintenance area into smaller units. Such divisions are common in air quality studies, most notably in connection with air quality modeling. When an array of square or rectangular units is used, one refers to this array as a "grid system" comprised of "grid cells" or "grid squares."

The problem in partitioning any area for EDZ is to choose the sizes of grid cells, and the spatial arrangement of grid cells and receptors, to account for various concerns of EDZ. So that these concerns may be better defined, the overall goals of EDZ are broken down into three categories with particular relevance to the gridding problem. These categories are maintenance of air quality standards, adequate consideration of existing and future land use patterns, and administration of EDZ. There is, of course, some overlap among these categories, but the distinctions provide a useful framework for discussion of the gridding problem. In the following discussion the specific concerns within each of these categories are presented, along with the specific gridding objectives suggested by them. Criteria for meeting each objective will then be presented.

Attention should first be drawn to EPA's *Guidelines for Air Quality Maintenance Planning and Analysis*, hereafter referred to as the *Guidelines*. Volumes 7,[1] 8,[2] and 13[3] are particularly relevant to the gridding concerns of EDZ, and the user should be familiar with the techniques described in them. Volume 7 presents methods for projecting pollutant emissions by counties, and Volume 13 describes how these emissions can be allocated to subcounty areas. Volume 8 presents a semiautomated (computerized) procedure for constructing an area source emissions inventory grid, based on population densities. A manual overlay gridding technique is also presented in Volume 13.

As noted previously, an EDZ analysis assumes the existence of studies such as those described in the Guidelines. If the grid system for the air quality analysis and the concurrent emission inventory are prepared in a manner compatible with the requirements of EDZ, a substantial amount of effort will be saved.

AIR QUALITY GOALS

The need for air quality maintenance planning is based on the likelihood that growth and development will lead to a violation of air quality standards. The key to maintenance planning with EDZ is to identify existing and potential problem areas and to set emission density limits in these areas sufficient to maintain air quality. Analyses of emission inventories and air quality monitoring data and estimates of growth in emissions are sources of this information. It is also necessary to relate emissions to ambient concentrations through the use of a diffusion model such as the Air Quality Display Model (AQDM).[6] Thus any grid system must meet the requirements of the diffusion model used to determine this relationship.* For example, AQDM requires that all area source grid cells be squares, and that all receptor locations have positive coordinate values.

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*AQDM is the only model currently capable of producing the source-receptor file (described in Section III) used as an input to the decision model. However, the Climatological Dispersion Model (CDM)[7] is being modified to generate such a file, and may be recommended by EPA for future applications. CDM currently imposes certain requirements on the grid system, and these requirements are likely to remain in force for any revised versions. These requirements are as follows: large grid cells must be integral multiples of the smallest grid cell in the array; the grid system outline must be rectangular; and, all grid cells must be squares. These

Grid cell side lengths should be between 1 and 8 km, as this size range allows for resolution of most data normally used for air quality planning.[6] Furthermore, grid cells should be of sizes that can be easily aggregated or subdivided. The easiest way to obtain a grid system that meets these requirements is to use side lengths of 1, 2, 4, or 8 km for all grid cells. The best method for preparing such a grid system is to overlay an array of 8 km x 8 km cells on the study area, and then to subdivide these cells according to the criteria presented below.

It is recommended that the Universal Transverse Mercator (UTM) coordinate system be used for grid registration since this system is widely used for other air quality planning purposes.

These considerations can be summarized in the first criterion for partitioning an air quality maintenance area:

1. Grid cells shall be squares with side lengths between 1 and 8 km, based in the UTM coordinate system. Additionally, they shall be of sizes that are easily aggregated and subdivided. In order to comply with this criterion, side lengths of 1, 2, 4, and 8 km are strongly recommended.

The grid system is the means for spatially allocating existing and projected area source emissions for modeling. Thus, grid sizes must be chosen that give adequate resolution of emissions. "Adequate resolution" simply means that the grid size must be small enough to prevent underestimating concentrations, but not smaller than the scale of the data and

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requirements also mean that any offset between grid cell boundaries (see Figure 1) must be an integral multiple of the side length of the smallest grid cell. In fact, the user should avoid offsets whenever possible, as they can lead to the use of small, inefficient dummy cells to "fill out" the rectangular boundary. If it is necessary for the user to fill out an existing grid system with zero-emission dummy cells to make it rectangular, the added grid cells should be as large as possible; e.g., even larger than the 8 km x 8 km limit imposed in the criteria. CDM's requirements strongly suggest use of the 1-2-4-8 gridding system described in the text.

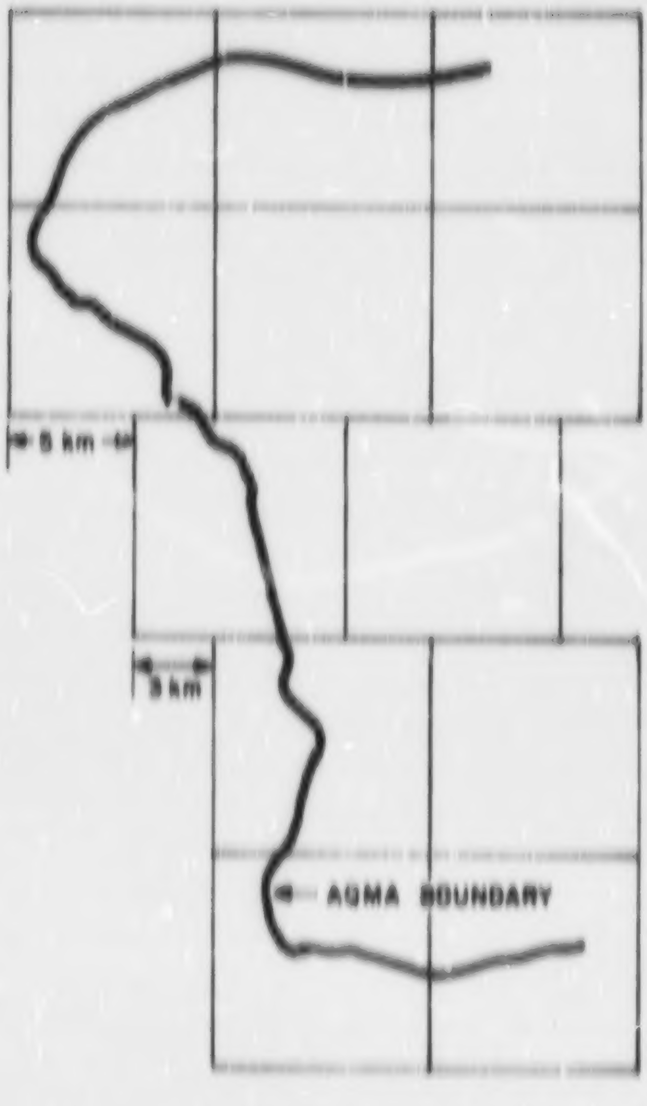
5 km
3 km
AGMA BOUNDARY

Figure 1. Offset gridding

modeling efficiencies will allow. Thus the higher the area source emission density, the smaller the grid size required to provide resolution.

Emission densities correspond to the intensity and type of development in an area. Industrial land uses typically emit more pollutant per hectare than residential or commercial uses, the high-rise residential development typically has a higher emission density than single-family houses on large lots.

In preparing the grid the user need not know actual emission densities. Instead, he may use other values as proxies, such as the values used to allocate emissions in maintenance planning analyses.[8] The most common such value is population. Emission densities for several land uses are considered to be directly related to population densities. One obvious exception to this relationship is industry. Industrial emissions are more typically related to employment, process volumes, or value added. However, since industrial emission densities are among the highest of any land use type, gridding can be simplified by applying the smaller grid sizes to heavy industrial areas. The user should keep in mind that a large part of industrial emissions may be point source emissions, which need not be reflected in the grid.

The following criteria are based on these considerations and allow the user to prepare a grid system that reflects likely emission densities.

2. Areas having an existing or projected population density greater than 2,000 persons per square kilometer should be contained in grid cells no larger than 1 km x 1 km.

3. Areas having an existing or projected population density between 1,000 and 2,000 persons per square kilometer should be contained in grid cells no larger than 2 km x 2 km.

4. Areas having an existing or projected population density between 200 and 1,000 persons per square kilometer should be contained in grid cells no larger than 4 km x 4 km.

5. Areas containing heavy industrial sources[a] that are not individually itemized in the emission density limit setting process should be contained in grid cells no larger than 2 km x 2 km.

The relationship between emission density and grid size also holds true for concentrations. High-concentration areas (i.e., those areas where concentrations are near the air quality standard) may be identified from isopleth maps based on monitored or projected concentrations at selected receptor points. Resolution of emissions is especially important in these areas, as great care must be taken in locating any new sources there. Therefore:

6. Areas in which existing or projected pollutant concentrations are 90 percent or more of the applicable air quality standard shall be contained in grid cells no larger than 2 km x 2 km.

Problems can still arise in areas having lower concentrations. It is possible that a given grid cell may have an existing or predicted concentration low enough to allow for a substantial amount of development. However, the spatial distribution of emissions within the cell may lead to a "hot spot" problem if all the development is clustered in a small area. Thus, if the cell is larger than 1 km x 1 km, it should be subdivided to reflect emission patterns more accurately. This requires that emissions be allocated to the grid cells. Then:

7. If the projected emission density of a grid cell in the system produced by criteria 1 through 6 is higher than the median value for the air quality maintenance area, and if by subdividing the cell into four equal parts and reapportioning emissions to the resulting cells, 40 percent or more of the total emissions for the original cell can be assigned to a smaller cell, the subdivision shall be incorporated into the grid system. This criterion clearly cannot apply to 1 km x 1 km grid cells.

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[a] For example, defined as Standard Industrial Classification (SIC) categories 26 through 33.[9]

The "hot spot" situation just described highlights the importance of another concern, the location of receptor points. Clearly a strategy like EDZ requires detailed information on emissions and concentrations throughout the air quality maintenance area. Therefore:

8. A model receptor point shall be located within each grid cell, preferably at the center. If an existing monitoring site is located within a grid cell, that site can be substituted for the receptor point to lower modeling costs.

One other consideration for receptor location must be mentioned. Because one of the goals of EDZ is maximizing the use of the assimilative capacity of the air, the decision model may tend to set higher emission density limits in grid cells near the outer edge of the air quality maintenance area. This happens because emission sources located in those areas have a smaller cumulative impact on air quality within the air quality maintenance area than those located in the center of the grid system. This is an undesirable outcome, as it may cause violations of the NAAQS if sufficient industrial development is planned for along the boundary of the AQMA, and regardless of the type of development, it may cause a violation of the allowable PSD[*] increment in the county adjacent to the AQMA. To be able to control this possibility, the receptor grid should be extended into the adjacent areas, as shown in Figure 2. Therefore:

9. In AQMA's where there is or may be substantial industrial development near the AQMA boundary, or where the adjacent area is a Class II or Class I PSD area, a row of receptor points shall be added at regular intervals around the outline of the grid system at a distance of not less than 4 km. It is recommended that these receptors be placed at what would be the center points of 8 km x 8 km grid cells, as illustrated in Figure 2.

Another air quality goal related to model receptor location is protection of sensitive receptors. The issues involved in identifying these receptors and setting air quality standards for them are presented in

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[*] Prevention of Significant Deterioration.

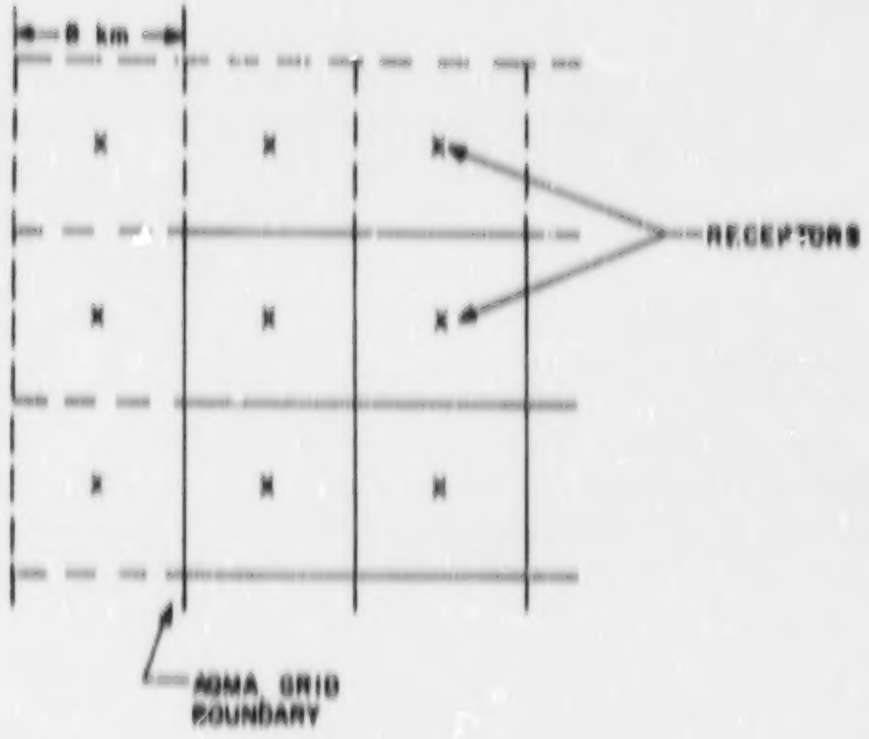
8 km
RECEPTORS
AQMA GRID BOUNDARY

Figure 2. Receptor locations outside an AQMA

Section III. If the user decides to protect sensitive receptors, receptor points representing them must be included in model runs. However, increasing the number of receptor points increases the cost and complexity of modeling. Therefore:

10. A receptor point shall be placed at the location of each sensitive receptor designated as "protected" by the implementing authority. Receptor points located under previous criteria may be substituted if they are located within 1 km of the sensitive receptor.

A final air quality goal with relevance to both gridding and receptor location is prevention of significant deterioration. As currently proposed, significant deterioration regulations will effectively require air quality standards more stringent than the NAAQSs to be met in designated areas. The standard will depend largely on the area's classification. Therefore:

11. A single grid cell shall not contain areas with different classification for significant deterioration requirements, unless at least one receptor point is located within each area.

It is quite likely that by following the above criteria, so many receptors are identified that in a large AQMA the computer resources necessary to execute the linear program for setting emission density limits may become prohibitive. Techniques for modifying the receptor grid to overcome this problem are discussed in Section VI.

LAND USE GOALS

From the discussion of air quality goals it is clear that land use patterns must be considered in the gridding process. Land use patterns serve as a proxy for emissions, and projections of future emissions must be based on future land uses. Furthermore, land use plans represent community preferences about development. For EDZ to be meaningful it must be implemented in a way that reinforces and is consistent with the land use plan; the grid system should reflect the patterns in that plan.

For the purposes of setting and administering emission limitations, the ideal grid would have a single land use in each cell. Otherwise, a single-number emissions limit must be translated into emissions limits for a number of source types, unless the community has no particular land use preferences in a given grid cell. Given the scale of most urban development and the size range of grid cells, isolating land uses with the grid is not practical. Ranking of land uses by their air quality impacts might be possible, but in most cases emissions result from a combination of activities. Considering these combinations, rather than individual land uses, in the gridding process will give better information about emissions, at least in urbanized areas.

However, it may be desirable in some cases to consider plans more explicitly, and to grid so as to separate incompatible land uses. An example might be a planned industrial area bordered by low density housing. While undue expansion of the industrial area can be effectively prevented with a low emissions ceiling for a large grid cell containing both uses, location of facilities within the cell is not directly addressed. If the cell were subdivided so that the two areas were placed in separate grids, limits could be set that would directly reinforce the desired development patterns.

"Incompatible land uses" must be identified from their differential air quality impacts, and not simply from the kinds of activities they represent if such a strategy is to be successful. Further, such a decision is most appropriately made by local jurisdictions. One obvious category of land uses to be included is sensitive environmental areas. If such areas are not otherwise protected, they can be separated from other land uses by grid boundaries, and appropriate emission limits can be set to prevent development of them.

Another feature of some plans is their consideration of natural boundaries to development, such as water bodies. Such boundaries can simplify gridding based on land use patterns. Grid cell subdivision is not necessary if an effective boundary already exists.

12. When the user judges it necessary he may separate incompatible land uses with grid boundaries. The decision should be based on applicability of other criteria, likelihood of conflicts over land use that may be resolved in a way detrimental to air quality goals, and the presence of natural boundaries that effectively limit the spread of a given land use.

ADMINISTRATIVE GOALS

EDZ can be implemented and enforced through any of a number of agency structures, and will require substantial interagency cooperation. Careful consideration of grid placement can help reduce the potential for such conflicts. In the California situation cited by Brail, et al.,[26] local jurisdictions were concerned with whether emissions limits assigned by the State Air Resources Board would be set for local jurisdictions or for grid cells. In such a situation it would clearly be desirable for each grid cell to be wholly contained within a single jurisdiction. Again, given the size range of grid cells this is neither efficient nor feasible. Rather, it may be desirable to identify areas of high conflict potential and to subdivide grid cells in these areas to fit jurisdictional boundaries as closely as possible.

For example, such a situation was encountered in the Louisville test of these criteria. The Indiana Port Commission has planned construction of an industrial area and port facility on the Clark County, Indiana shore of the Ohio River, located within the Louisville Interstate air quality maintenance area. The Kentucky shore and an island in the River opposite the proposed site are used for recreational purposes, and Kentucky is opposed to development of the facility.[10] It would clearly be desirable to have grid boundaries conform to state boundaries in this case, but the grid scale makes it unlikely. Emission density limits can be set for any grid cell spanning the state boundaries, based on both states' regional land use plans. Once these limits have been set, allocation of emissions to each portion of the grid cell may be done on the same basis. Disputes between the states might then be settled by some negotiating procedure. The point is simply to facilitate such negotiations by subdividing grid cells in such areas to the smallest allowable size.

> 13. If a single grid cell spans jurisdictional boundaries and the potential for conflicts between jurisdictions over land uses in the grid cell is high, the cell shall be subdivided until each grid cell is contained as nearly as possible within a single jurisdiction.

A second general administrative goal is to simplify the process of regridding in response to developments in the air quality maintenance area. First, the need to regrid will be minimized by meeting the gridding criteria in the first gridding effort. Second, the criteria must also be observed for any regridding effort, and hence provide guidance as to when regridding is necessary; e.g., for obtaining adequate resolution of emissions. Finally, selection of grid sizes that can be aggregated or subdivided easily will make regridding simpler.

> 14. Grid boundaries shall be redrawn whenever changing conditions cause any of the criteria to be violated.

In any administrative situation minimizing costs is important. Since the criteria are designed to simplify the process of implementing EDZ, meeting them should help minimize costs. Since cost (especially modeling costs) is partly dependent on the number of grid cells, unnecessary subdivisions should be avoided. For example, the gridding technique in Volume 13 of the Guidelines requires that the user subdivide grid cells until each portion of the air quality maintenance area for which allocation data are available is contained as nearly as possible within a single grid cell.[11] This may be unnecessary for achieving adequate resolution of emissions for EDZ. Therefore:

> 15. A cluster of adjoining grid cells may be aggregated if the resulting cells do not violate any of the previous criteria.

SECTION III

CRITERIA FOR SETTING EDZ LIMITS

The relatively long-term nature of air quality maintenance requires that those measures used to ensure maintenance be as compatible as possible with overall community goals. Air quality is oftentimes not as tangible an objective as other public desires and is thus open to perhaps closer scrutiny than more tangible desires such as more jobs. It is for these reasons that considerations other than air quality must also be included in setting EDZ limits.

The following discussion has two objectives. First, the criteria that planners are likely to require are identified. Secondly, these criteria are expressed in terms compatible with the decision model used to set emission density limits. Four groups of goals from which criteria can be developed have been identified and are discussed in turn. These are economic goals, air quality goals, land use and environmental planning goals, and administrative goals.

The discussion assumes the reader's familiarity with the basic terminology of linear programming, as this is the technique used to set emission density limits.* Some criteria have thus been formulated as objectives or constraints.

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*The reader unfamiliar with linear programming is referred to Appendix A, which is a brief introduction to the subject.

ECONOMIC GOALS

The economic goals of any region are, in the general sense, well known and often stated. In a word, prosperity is sought. Economic prosperity is typically identified with high levels of employment, stable prices and tax levels, and a diversity of economic activity. EDZ is likely to influence the location, density, amount, and type of industrial activity in the region. Therefore, criteria in this area must be established.

Emission density limits can affect urban development either by precluding certain types of activity altogether or by necessitating controls for new establishments. Therefore, accounting for these impacts will require two kinds of information. First, the user must have some idea of the amount of growth expected to occur during the period covered by the maintenance plan, and how the growth will be distributed across the air quality maintenance area. The best sources of this information are the land use element of the comprehensive regional plan(s) applicable to the air quality maintenance area, and local plans and zoning. These plans and regulations reflect community preferences and expectations about growth, and the emission density limits should reflect the amount and location of growth called for in them. To accomplish this, the user must define a value for the projected maximum emissions (without EDZ) from a given site for the last year of the planning period. These values can then be used in the decision model in various ways, depending on the formulation the user selects.

In most instances the user cannot determine exactly which industry or other development will locate where in a region. For example, most planning and zoning schemes include only one or two industrial land use categories; e.g., heavy and light, or general and permitted. Therefore, the user should select those categories within each land use category that are expected to show the most growth as prototypes for calculations of future emissions.

With this information, emission density limits can then be set by maximizing the aggregate emission loading in the region, given the projected land-use growth. Emission density limits would thus be set, while keeping within the bounds of minimum and maximum feasible rates that will allow the development specified in the land-use plan, in a manner that allows the greatest amount of emissions consistent with the NAAQs. One assumes that facilitating the maximum emission loading in a region is loosely synonomous with facilitating the maximum amount of economic growth consistent with the NAAQSs. Note, however, that in some areas whose economic base consists of little high emission density industry, it may not be true that maximizing potential emission loading will help economic growth.

The second kind of information that may be required is control costs. These costs vary by industry, process, and control efficiency, and should also be estimated for prototype industries. They are most useful when expressed in their incremental form; i.e., the cost per unit of emission reduction. If resources permit this information to be obtained, emission density limits can be set that will reflect the cost of controls for the projected level of activity. Such costs would be expected to vary with the location of activity within an air quality maintenance area, simply because the degree of control needed for a given source would vary from location to location. Thus emission limits can be established that represent the least control cost development pattern from an air quality maintenance perspective, given a desired or projected level of economic and demographic activity.

Economic goals can thus be summarized in the following criterion.

1. Emission density limits shall reflect the costs of emission controls associated with the desired level and location of economic activity for a community, or shall reflect the maximum amount of emissions in the region consistent with the NAAQSs.

AIR QUALITY GOALS

For the purposes of this report EDZ has as its primary goal the maintenance of NAAQSs for particulate matter and sulfur oxides. Emission density limits must be set low enough so that predicted concentrations of these pollutants do not exceed the standards. This means that the user must know the relative air quality impact of each existing and potential source at every receptor point in the air quality maintenance area. This impact is determined by the location of the source relative to the receptor and by the variables that influence the atmospheric dispersion of pollutants.

However, emissions from inventoried sources in an air quality maintenance area are not the only components of concentrations at a given receptor point. Background concentrations resulting from sources outside the air quality maintenance area are one component; fugitive emissions that are not inventoried within the air quality maintenance area are another. These values must be accounted for before emission density limits can be set.

Existing background and fugitive components are often assumed to be accounted for by "statistical" calibration of the model.* Calibration is accomplished using simple linear regression, so that predicted concentrations are adjusted by the formula

$$\hat{X} = A + BX \qquad (1)$$

where X is the predicted concentration.

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*The statistical validity of the calibration process is discussed in two monographs by Brier.[16,17]

Calibration is discussed elsewhere in more detail,[12] and the user should refer to these discussions if he is unfamiliar with the technique. The intercept A should include the background and fugitive concentration components, and can simply be subtracted from the standard being used to set emission limits for the pollutant in question.

Future background and fugitive components may be larger or smaller than existing values. The user must attempt to estimate the changes in these values and to adjust the concentration standards accordingly. Projected increases would have to be subtracted from the standards, but decreases might be held in reserve by the implementing agency as a safety factor.[*]

In any case a safety factor or reserve should be available for several reasons. Unusual meteorological conditions or unanticipated increases in background or fugitive emissions could lead to violations of the standards. Error in the modeling process could lead to underprediction of concentrations. Finally, changes in the land use plan are likely to occur over time. In order to avoid rerunning the decision model for small changes, the implementing authority should have a reserve concentration increment available so that variances can be granted. This point is discussed in more detail in Section IV.

In summary, the primary air quality constraint can be expressed as:

$$\sum_{j} \sum_{k} t_{i,j,k,\ell} \sum_{m} (E_{j,k,\ell,m} \;\; a_{j,k,m}) \leq X_{i,\ell} = b_{i,\ell} - f_{i,\ell} - p_{i,\ell} - r_{i,\ell}$$

$$= S_{i,\ell} \;\Big|\; \text{for all } i,\ell \qquad (2)^{\dagger}$$

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[*] At this time there is no approved methodology for inventorying fugitive emission let alone projecting them. As methodologies are developed, they should be used. Background concentrations are best estimated by regional air quality planners familiar with the area and a specific methodology is not given here. To the extent that these components of the emission inventory are omitted, the calibration intercept may account for them. If substantial sources are uninventoried, it may be prudent to project the calibration intercept to the design year by the population forecast to account for growth in these sources.

[†] The variable definitions shown in Table 1 are employed.

This states that the emissions at a source and the transfer coefficient between that source and a specified receptor, summed over all sources, shall not exceed a certain critical value. The critical value is calculated by subtracting the concentration at the specified receptor due to emission sources not in the EDE limit setting model from a desired air quality standard. There would be a similar constraint equation for each receptor.

The transfer coefficient, $t_{i,j,k,l}$ is derived from executing AQDM. This relates annual emissions to annual mean concentrations (i.e., long-term standards). It is sometimes referred to as χ/Q or the coupling coefficient. A method for considering short-term standards is discussed in Appendix B.

There may be state or local air quality standards in an air quality maintenance area that are more stringent than the NAAQSs. These can simply be entered in place of the NAAQSs in the formulation if they are expressed in the same way for the same pollutants. State and local ambient air quality standards may be expressed for different averaging times and with different definitions of violations; e.g., a 4-hour particulate concentration standard not to be exceeded more than once a month. State and local agencies should have sufficient experience with such standards to be able to make them compatible with the model. Another air quality goal to which EDE must be applied is prevention of significant deterioration. This effectively means that more stringent air quality standards must be met in designated areas. The standards as currently proposed[13] are expressed in terms of an allowable concentration increment for each designated area of a certain class. The implementing agency might want to phase the use of this increment over time to prevent its being rapidly used up in a way that limits development opportunities. Thus, the standard on which emission limits are based would represent that portion of the allowable increment to be used during the period in question.

Yet another potential air quality goal that may or may not be codified is protection of sensitive receptors, namely persons, plants, or materials whose susceptibility to air pollution warrant their protection with more stringent air quality standards. Previously, a criterion was presented requiring model receptor points to be located at any sensitive receptor that the user would want to protect. Concentration limits sufficient to protect these receptors could then be assigned to these points in the process of setting emission limits. The process would involve several steps. First, the user would have to define which receptors would be protected, as the number of possibilities could be large. Then concentration limits sufficient to protect the designated receptors would have to be established. These could be based on information about pollutant effects, or, if such information is difficult or costly to obtain, on some arbitrarily defined "safe" value; e.g., the significant deterioration increment for a Class I area. Whatever the method used, the standard selected would simply be used in place of the NAAQS for the designated sensitive receptors. In deciding which sensitive receptors to include, the user should keep in mind that increasing the number of receptor points increases the cost and complexity of modeling, and that any tightening of air quality standards will impose additional costs on the community.

2. Emission density limits shall be sufficient to maintain the NAAQSs and any standards based on significant deterioration requirements and community air quality objectives. The standard shall be adjusted to account for background concentrations, fugitive emissions, and a safety margin selected by the implementing authority.

A final technical issue involved in setting limits is the question of stack heights. Clearly, the user will not know exact stack heights for future sources and must thus make certain assumptions. The usual practice is to assume a standard stack height for all area sources of a given type (i.e., industrial and nonindustrial types), which applies to existing and future sources. For future point sources the following criterion should apply:

3. A conservative stack height for all future point sources shall be assumed for modeling purposes, based on state and local minimum-stack-height regulations and on existing sources of the same category in the base year emission inventory.

LAND USE AND ENVIRONMENTAL PLANNING GOALS

The comprehensive planning process normally involves consideration of several sets of goals, which, when taken together, define the desired development pattern for a community. These goals include those on economic development and housing, public service, environmental quality, and transportation.

Because EDZ is a factor in land-use decisions, and especially in industrial location decisions, it will affect travel patterns in an air quality maintenance area. It is necessary to account for this effect in setting emission density limits. Land use plans normally account in some way for travel patterns, especially those resulting from work trips. Future land uses shown in plans are determined in part by access to transportation. There may be a transportation control plan that imposes a limit on travel. Emission density limits can be set to account for these concerns if they are reflected in the land use plan.

EDZ affects land use patterns because different land uses have different emission characteristics. Emission density limits must thus be set for each land use type in each grid cell. Furthermore, the land use types for which limits will be set must be those defined in planning and zoning documents, as these are the categories for which future locational information is available. This allows the user to tailor the emission limits to conform to the land use pattern presented in the plan.

Tailoring of emission limits can be accomplished in two steps. First, in each formulation of the limit setting model, the emission limit is weighted by the land area available to each source category in a grid cell, based on the regional land use plan. Secondly, the emission limits must reflect the emission characteristics of the given land uses. For example, in the emissions maximization model (Model No. 1 of Section V), if emission limits were based on planned areas alone, a residential area might receive a higher limit than an industrial area in the same grid cell. This situation can be prevented by setting minimum emissions for each land use type in the grid cell based on the planned or projected activity levels for that land use. These minimum emissions would correspond to the minimum feasible emissions constraint used in Model No. 1.

Furthermore, certain land uses might be prevented from locating in an area by setting maximum limits low enough to make control costs prohibitive. If, for example, a residential area is to be protected against industry, a limit might be set low enough to preclude any industrial location there. If no development is to be allowed in a given area in order to protect certain resources, emissions from that area would not be allowed to increase at all.

EDZ can also be used to aid in the attainment of environmental goals expressed in the land use plan. For example, water quality management might be aided, as development types and densities relate to waste loads entering streams. Water quality planning information might be used to place a limit on the amount of development occurring in various locations in a basin over a given period, depending on the phasing of construction of treatment facilities. EDZ limits could then be set to reflect the corresponding level of development.

These concerns can be summarized in the following criteria:

4. Emission density limits shall be set for individual land use types within a grid cell. The land use types selected shall be those for which future location data are available; i.e., existing planning and zoning categories. Since the numbers and definition of these categories are likely to vary from municipality to municipality, for uniformity and modeling efficiency they should be placed within broader groups. A suggested grouping follows:

rural/open space
low density residential
high density residential
commercial/office
institutional/service
light industry
heavy industry.

5. Emission density limits shall reflect development patterns congruent with the land use and environmental planning goals of the community, which are expressed as land use or development plans or as policy statements. This may be accomplished by setting limits that bar certain sources; i.e., land use types, from a given area, or encourage their location in other area.

ADMINISTRATIVE GOALS

Some administrative concerns of EDZ have been mentioned previously, such as reserving a concentration safety margin to avoid model reruns. A major administrative goal that was mentioned previously in relation to gridding is conflict minimization. The implementing agency will have to balance some competing interests in the process of setting limits. By meeting the other criteria presented in this section, the agency can hopefully enter the goals of these interests into the decision model.

Some issues will remain to be resolved. One goal that should be addressed directly is minimum interference with growth patterns. This goal is partly met by using emission limits to reinforce the land use plan. However, it is possible that the decision model could set very different emission density limits for similar land uses in adjoining grid cells. The user should guard against this by requiring that a cluster of parcels of a given land use type has the same emission density limit over its whole area.

This might be expressed as a model constraint in the following way:

$$E_{j,k,\ell,m} - E_{j+\Delta,k,\ell,m} = 0 \mid \text{for certain } \Delta \text{ and } j; \qquad (3)^{*}$$

or as a criterion.

6. When contiguous areas of the same land use type are contained within separate grid cells, emission density limits for the two areas shall be equal.

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[*] The user must manually identify each j and Δ. If any grid cell has no area in a particular land use class, it cannot be identified in this constraint. That is, where $a_{j,k,m} = 0$ or $a_{j+\Delta,k,m} = 0$, the constraint is meaningless.

SECTION IV

CRITERIA FOR REVISING EDZ LIMITS

Once emission density zoning limits have been set (i.e., emissions quotas have been allocated to grid cells) and implemented, several conditions may arise that require the revision of the prescribed emission limits. These conditions can be categorized as

- those arising from unexpected community growth
- those arising from significant changes in community goals (e.g., transportation and land use plan revisions)
- those arising from unexpected changes in the technological, administrative, or economic precepts of the emission density limit setting decision model; e.g., changes in fuel prices, changes in state or federal regulations, or unplanned closings or openings of major emission sources.

The differences in the scope and influence of these conditions suggest the application of different methods of revising emission density limits. In general, small changes can be accommodated through variance proceedings; only in the event of major changes in these conditions should the limits be revised globally.

In addition, whether a market is instituted for the exchange of emission rights will significantly limit the frequency and extent of emission limit revisions. A market for emission rights will depend on a stable inventory of emission limits to be orderly and fair.

Criteria for revising limits with and without an emission rights market are outlined separately below.

CRITERIA FOR REVISING LIMITS WITHOUT AN EMISSION RIGHTS MARKET

In defining the original set of emission density limits, one will use the best information available on existing emission sources, community growth plans, control costs, etc. However, it is almost certain that this information is imperfect. One should expect unforeseen and undesired hardships imposed on individual firms. For an emission density zoning control strategy to be equitable, and perhaps legal, one must be able to ameliorate these hardships by revising the emission density limits in individual cases; i.e., by granting of variances. To be able to grant a variance without violating the air quality standards, a reserve is required. Therefore,

1. The emission density limits shall be set with a reserve concentration at each receptor.

2. To provide for orderly community growth and unanticipated individual hardship situations, a quasi-judicial air pollution control board or similar institution shall be empowered to grant variances to emission density limits from time to time. Variances could be granted either to individuals for specific sites or to municipalities for allocation among sites in component areas. An individual would need the endorsement of the appropriate municipality. In each calendar year, up to 10 percent of the remaining reserve at each receptor could be allocated in such a manner.

3. Changes in conditions that lower emission levels will be treated on an individual basis, with the reduction in emissions in a particular component area accruing to the air quality reserve at each receptor.

A revision to the transportation and land use plans may alter the configuration of the emission sources. If the revised plans are based on new demographic and economic projections, the total quality of projected emissions may change as well. If these changes are significant, it will be necessary to revise the emission density limits globally.

4. After a significant revision in the transportation and land use plans, the emission density limits will be redefined according to the criteria for setting emission density limits.

5. Existing emission densities at the time of a plan revision will be used as a lower bound on the redefined emission density limits.

Aside from individual variances, unplanned closings of major sources, and plan revisions, other unexpected changes in the technological, administrative, or economic assumptions of the emission density limit setting process may occur. For example,

- a New Source Performance Standard that was promulgated or projected to be promulgated may be rescinded, or
- (in the event the control cost minimization objective function is employed) changes may occur in the costs of various control devices or in the relative prices of fuels.

Such unexpected changes may alter the optimal mix of emission density limits. If the changes are of a large magnitude, it would be desirable to revise the limits globally. If the changes are small or affect only a small number of sources, it would be less disruptive to grant variances to the appropriate sources. While the threshold between the two possible reactions would have to reflect the experience of the control agency,

6. Sensitivity analysis should be used when a change in the assumptions that were used in setting the limits occurs. If the sensitivity analysis indicates a significant, say more than 20 percent, change in the optimal solution for more than 10 percent of the sources, then the limits should be reset according to criteria 4 and 5. Otherwise, the sources could be treated on an individual bases according to criterion 2.

CRITERIA FOR REVISING LIMITS WITH AN EMISSION RIGHTS MARKET

The ability of a private or public emission rights market to provide for orderly community growth, changes in fuel prices, and variances from original limits in individual cases markedly limits the revisions in emission limits that would have to be implemented by a control agency. In fact, only when a major revision is made in the land use plan would a control agency have to consider the global redefinition of the EDZ limits. That redefinition would be accomplished according to the criteria outlined previously. Otherwise, one could depend on the market to provide for the requisite changes in emission limits, subject to the following criteria.

1. Emission rights may be transferred between parcels within a component area on a one-to-one basis.

2. Emission rights may be transferred between parcels in different component areas according to the following relationship:

$$\Delta \dot{e}_y = \frac{\Delta e_x \, t_{x,i}}{t_{y,i}} \quad \Bigg| \text{ the smallest over all } i \tag{4}$$

where $\Delta \dot{e}_y$ is the change in emissions in the new component area

Δe_x is the change in emissions in the old compartment area

$t_{x,i}$ is the transfer coefficient from source x to receptor i

$t_{y,i}$ is the transfer coefficient from source y to receptor i.

This is based on the identity,

$$|\Delta e_y \, t_{y,i}| = |\Delta e_x \, t_{x,i}| \tag{5}$$

In other words, there is some increase in emissions Δe_y in component area y, whose resulting increase in concentration at receptor i will exactly balance the reduction in concentration at receptor i due to the decrease in emissions at x. If, over this set of emission increases, $S(\Delta e_y)$, the smallest value of Δe_y, the amount, $\Delta \dot{e}_y$, is permitted to be transferred to component area y, then concentrations at all receptors will not increase due to the transfer. The corresponding Δe_x is subtracted from the old component area.

3. After a transfer between component areas according to criterion 2, the incremental decrease in concentrations at receptors other than the binding receptor; i.e., the receptor i for which Δe_y is the smallest, would accrue to the control agency as a reserve.

   For each receptor i, except for the binding receptor(s), this reserve would be

$$R_i = t_{y,i} (\Delta e_y - \Delta \hat{e}_y)$$

$$= \Delta e_x t_{x,i} - \Delta \hat{e}_y t_{y,i} \qquad (6)$$

4. To facilitate orderly community growth, portions of the reserve at each receptor (the sum of the initial reserve that was set aside when emission density limits were first set and any increment due to transactions of emission rights between component areas) should be auctioned in a public market at appropriate time intervals. For example, 50 percent of the remaining reserve could be sold every 10 years or after a major change in the transportation or land use plans.

A control agency could publish a matrix of minimum values of the $t_{x,i}/t_{y,i}$ ratios. A source wishing to buy emission rights then could search for high values in the appropriate row (or column) to find the potentially best bargin. On the other hand, a source wishing to sell emission rights could search for high values in the appropriate column (or row) to find the potentially best prospective purchaser.

SECTION V

SPECIFICATION OF DECISION MODEL

The selection of a decision model for setting emission density limits in an AQMA must rest with the individual agency implementing an EDZ maintenance strategy. The choice of a particular model will represent the resolution of the tradeoff between a specific agency's concerns and available resources. Four candidate formulations are described in the following sections. These formulations differ in their objective functions; i.e., exactly what is being maximized or minimized. The possibility of other objective functions is discussed. Next, several variants of the first formulation, emissions maximization is described. While each variant does maximize emissions, they each treat the constraint set slightly differently.

The simplest model is the maximization of emissions. This formulation is the most inexpensive model formulation to implement in terms of both data requirements and computer time. Given the community goals expressed in the land use element of the regional plan, it will allocate emission rights to component areas in a pattern that maximizes the aggregate emission loading in a region and still maintains ambient air quality standards. The assumption implicit in this formulation is that the maximization of emissions is closely related to the maximization of economic activity permitted by the NAAQSs. Within the limits of the upper and lower bounds on emission density limits[*], the maximization of emissions implicity values emissions from different land use categories[‡] in the same component area identically. That is, if both sources are not at their upper or lower bound, several alternate optimal solutions are possible since the transfer coefficients are identical.

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[*] That is, the zero cost and technological constraints.

[‡] For example, light industry and commercial land use.

More significantly, in the case of one binding receptor (which was the case in the Baltimore TSP test run and was closely approached in the other tests), the emissions maximization formulation implicitly values emissions from different areas of the region, weighted by the reciprocal of their transfer coefficients as having equal value. An example will clarify this condition. Assume two emission sources, whose emission density limits, in tons per year per acre, are E_1 and E_2. Their transfer coefficients (X/Q) to a certain receptor are, respectively, 0.5 and 0.1 $\mu g/m^3$/ton/year and their areas of the emission sources are both 2 acres. Mathematically, the linear program may be stated as

$$\text{Maximize emissions, } E = 2\,E_1 + 2\,E_2 \tag{7}$$

$$\text{such that} \quad (0.5)\,(2)\,E_1 + (0.1)\,(2)\,E_2 \leq S$$

where S is the desired NAAQS. In the maximization of emissions then, the linear program will implicitly value 5 tons of emissions from source 2 as equivalent to 1 ton of emissions from source 1 for the purposes of meeting the air quality constraint. The linear program would assign a higher emission density limit to the second source regardless of the control cost schedules (or other costs) of the two emission sources. The remaining three decision models attempt to value the emissions from various sources according to the location and type of emission source.

The premise behind the control cost minimization formulations (the second and third models) is that for two emission sources with equal transfer coefficients (χ/Q) to a critical receptor, the emission source with the higher incremental control costs should be required to meet a less stringent standard. The goal of this formulation is to set a pattern of emission density limits such that, if the region is developed to the levels specified in the regional land use plan, the individual source's incremental control cost of reducing the ambient air concentration at a critical receptor would be identical with that of all other sources. With suitable constraints, the minimization of control costs is equivalent to maximizing emissions weighted by control costs. It is an attempt at a cost effective approach to setting EDZ limits.

The final model is the maximization of emissions weighted by land value (model no. 4). There are several reasons why it may be preferred to the second and third models. First, land value represents the upper bound on control costs, and in some situations may be easier to obtain than other control cost data. An individual source is faced with several options in complying with an EDZ ordinance. One, of course, is the installation of control equipment in addition to that required by other existing regulations. Another possibility is the reduction of the emission density. This means, in effect, that some of the site must remain comparatively underutilized (not developed to the firm's desired emission generating capacity). The cost of the underutilized land, therefore, is one form of control cost facing the firm. However, because there appears to be no clear theoretical justification for using maximum control cost — land value — as opposed to average or minimum control cost in the model, some users may prefer the second or third model. Second, because land costs tend to be higher in the center of a metropolitan area, this formulation will not exhibit the tendency of the emissions maximization formulation to set high emission density limits on the urban fringe. (Model No. 1 does this because the critical receptors tend to be in the center of the metropolitan area.) Even though the land use plan may restrict intensive development on the urban fringe, the emissions maximization model, as opposed to model no. 4, will encourage near suburban industrial development to the detriment of expansion of existing core city industrial facilities and redevelopment of core city industrial sites. Third, model no. 4 may reduce the potential disruption of existing land use patterns caused by the introduction of EDZ. The relative value of a parcel is taken as a partial indicator of that parcel's rightful share of the bundle of emission rights available to the region. High value property would receive higher emission limits than low value property, other things being equal. Model no. 4, therefore, would perturb the already existing value ranking of land as determined by market forces the least, and presumably change the location and timing of future development the least. This is done at the expense of the total emissions in the region.

Aside from the four models described below, others are possible. The user is limited only by the resources and ingenuity of the implementing agency. The models would be basically the maximization of emissions weighted by some parameter; e.g., control cost, land value. Within this format, other formulations can easily be specified if they more adequately reflect the goals of the community and if the requisite data are available. The four models are presented below. Variable definitions are shown on Table 1.

MAXIMIZATION OF EMISSIONS (MODEL NO. 1)

Maximizing emissions is relatively the most straightforward formulation of an objective function. The most specious relationships to specify are the SO_x-PM feasibility constraints, which ensure that a very stringent emission density limit for one pollutant and a relatively lax unusable limit for the other pollutant are not set in the same cell. The linear program may have to be run several times as this approximation is fine tuned. The necessity of this constraint and the estimation of its parameters are discussed in Appendix C. The formulation of Model No. 1 is as follows:

$$\text{Maximize emissions} = \sum_j \sum_k \sum_l \sum_m E_{j,k,l,m} \, a_{j,k,m} \qquad (8)$$

Table 1. DEFINITIONS OF VARIABLES USED IN SECTION V

SUBSCRIPTS

i = receptor index

j = grid square or point source index

k = land use class index

ℓ = pollutant species index

1. particulate matter
2. sulfur oxides

m = current and growth index

1. existing sources
2. future sources

n = 1,2 . . . for each potential emission rate (tons/year)

PARAMETERS

$a_{j,k,m}$ = the land area of emission source j,k,m for existing sources ($m = 1$), obtained from base year land use inventory, and for future sources ($m = 2$), obtained from land use plan

$b_{i,\ell}$ = the projected concentration at receptor i of pollutant ℓ due to background

$c_{k,\ell,m}$ = the incremental control cost incurred to reduce emissions from land use category k. Obtained from execution of IPP.*

$c^{land}_{j,k}$ = the cost of land for land use type k in grid square j; or for point source j

$c'_{j,\ell,n}$ = the control cost incurred at source j to emit at the emission rate indexed by n, i.e., at emission rate $e_{j,\ell,n}$

$e_{j,\ell,n}$ = for each source j, the set of possible emission rates, indexed by n

$e^{max}_{j,k,\ell,m}$ = the maximum feasible future emission density after application of existing and planned regulations for existing sources ($m = 1$), obtained from AQMP projection; for future sources ($m = 2$), obtained from floor area ratio and emission factors

$e^{min}_{j,k,\ell,m}$ = the minimum feasible design year emission density (defined only for $m = 2$)

$e^{base}_{j,k,\ell,m}$ = the base year emission density (defined only for $m = 1$), adjusted for current and pending emission control regulations.

$E_{j,k,\ell,m}$ = the emission density limit, the variable that is set by the EDZ limit setting model

Table 1 (continued). DEFINITIONS OF VARIABLES USED IN SECTION V

$f_{i,\ell}$ = the projected concentration due to fugitive emissions for receptor i (usually defined only for ℓ = 1)

$m_{i,\ell}$ = the projected concentration at receptor i of pollutant ℓ due to mobile sources

$r_{i,\ell}$ = safety margin or reserve

$p_{i,\ell}$ = the projected concentration at receptor i of pollutant ℓ due to power plants and other sources not considered in the emission limit model

$t_{i,j,k,\ell}$ = the transfer coefficient, the incremental air quality impact at receptor i of source j, land use class k, for pollutant ℓ. Obtained from AQDM

μ_k, ν_k = coefficients relating the minimum possible levels of particulate matter emissions for a given sulfur oxide emission level, and the converse

$x_{i,\ell}$ = the reverse calibrated standard, pollutant ℓ, receptor i

$\delta_{j,\ell,n}$ = a zero-one variable

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[a] The Air Quality Implementation Planning Program (IPP) determines control costs for point sources given emission limits. See TRW Systems Corp. Air Quality Implementation Planning Program. 2 volumes. Environmental Protection Agency, Research Triangle Park, North Carolina. November, 1970.

subject to:

air quality constraint: $\sum_j \sum_k t_{i,j,k,\ell} \sum_m (E_{j,k,\ell,m} \;\; a_{j,k,m})$

$\le X_{i,\ell} - b_{i,\ell} - f_{i,\ell} - r_{i,\ell} - p_{i,\ell} - s_{i,\ell} \,|$

for all i,ℓ

attainment constraint: $E_{j,k,\ell,m} \le e^{base}_{j,k,\ell,m}$ | for all j,k,ℓ; for $m = 1$

proximity constraint: $E_{j,k,\ell,m} - E_{j\pm\Delta,k,\ell,m} = 0$ | for certain Δ and j

zero cost constraint: $E_{j,k,\ell,m} \le e^{max}_{j,k,\ell,m}$ | for all j,k,ℓ,m

technological constraint: $E_{j,k,\ell,m} \ge d^{min}_{j,k,\ell,m}$ | for all j,k,ℓ,m

SO_x-PM feasibility
constraint:

$$E_{j,k,\ell,m} - (u^b_k E_{j,k,\ell,m}) \ge u^a_k$$

$$E_{j,k,\ell,m} - (v^b_k E_{j,k,\ell,m}) \ge v^a_k$$

for ℓ = PM in each first term
for $\ell = SO_x$ in each second term
for all j,k,m

The objective function is the sum of the total emissions in the region; i.e., the sum of the products of each source's emission density limit and its area. The first constraint is the air quality constraint. The sum of the products of emissions at each source and its transfer coefficient represents the ambient concentration at the specified receptor due to sources controlled by EDZ. This must be less than the NAAQS after subtracting the concentration due to mobile sources, fugitive dust, power plants, background, etc. There is a separate constraint equation for each receptor and pollutant.

The attainment constraint indicates that an existing source shall not have an emission density limit assigned to it that is less than its existing emission density (after considering compliance schedules and other planned emission controls). This places the maintenance burden on future sources and capacity expansion of existing sources. The possibility of not doing so is discussed in Appendix E. There is a separate constraint equation for each existing source.

The proximity constraint allows one to require emission density limits in adjoining component areas to be identical. It permits one to set identical emission density limits for all the grid cells in a political subdivision; e.g., municipality, township, to facilitate the administration of EDZ.

The zero cost constraint specifies an upper bound on the emission density limit for each source. The upper bound is the maximum emission density that may be expected for that source in the absence of EDZ. It implies that no control equipment beyond what is already required by other regulations would be installed; hence, it is the point where the firm incurs no additional costs due to EDZ.

It is necessary to include an upper bound on all sources; otherwise, the linear program will assign an excessively high and unusable emission density limit at a few sources that have the smallest transfer coefficients to the critical receptors.* In similar manner, the technological constraint specifies the minimum emission density for each source that is technologically or economically feasible.

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*This occurred by accident in preparing the Louisville TSP test case. Several sources had their upper limits omitted. The linear program maximized emissions by setting most sources at their lower limit and assigning an emission density limit of 2456 tons/day/km^2 at one source that had no upper limit! In the same run, several sources also had their lower limits omitted by mistake. Their emission density limits were set at zero.

MINIMIZATION OF CONTROL COSTS (MODEL NO. 2)

The minimization of control costs is formulated as follows:

$$\text{Minimize } C = \sum_{k}\sum_{\ell}\sum_{m} c_{k,\ell,m} \sum_{j} a_{j,k,m} \left(e^{\max}_{j,k,\ell,m} - E_{j,k,\ell,m}\right) \qquad (9)$$

subject to:

air quality constraint: $\sum_{j}\sum_{k} t_{i,j,k,\ell} \sum_{m} (E_{j,k,\ell,m} \; a_{j,k,m})$

$\leq S_{i,\ell} - b_{i,\ell} - f_{i,\ell} - v_{i,\ell} - p_{i,\ell} - n_{i,\ell}$

| for all i,ℓ

attainment constraint: $E_{j,k,\ell,m} \leq e^{\text{base}}_{j,k,\ell,m}$ | for all j,k,ℓ; for $m = 1$

proximity constraint: $E_{j,k,\ell,m} - E_{j+\Delta,k,\ell,m} = 0$ | for certain Δ and j

zero cost constraint: $E_{j,k,\ell,m} \leq e^{\max}_{j,k,\ell,m}$ | for all j,k,ℓ,m

technological constraint: $E_{j,k,\ell,m} \geq e^{\min}_{j,k,\ell,m}$ | for all j,k,ℓ,m

It should be noted that this is equivalent to maximizing emissions weighted by control costs, viz.,

$$\text{Maximize } E' = \sum_{k}\sum_{\ell}\sum_{m} c_{k,\ell,m} \sum_{j} a_{j,k,m} E_{j,k,\ell,m} \qquad (10)$$

subject to the same constraints.

The major difficulty in using this formulation, as well as the next one (Model No. 3), is the specification of the control cost parameter, $c_{k,\ell,m}$, the incremental annualized cost per ton per day of an emission reduction at each source. A method for specifying the parameter is discussed in Appendix D. However, the estimation of control costs of future emission sources is tenuous at best. If, in a given application, they cannot be estimated with some confidence it may be prudent to use the simpler emissions maximization formulation.

ALTERNATIVE FORMULATION OF CONTROL COST MINIMIZATION (MODEL NO. 3)

Rather than forcing control cost to be a linear parameter, one can recognize its nonlinear and discrete nature. Through the use of integer programming, one can directly minimize control costs, control costs being defined as a set of costs associated with each of the possible emission levels. The formulation is as follows:

$$\text{Min } C' = \sum_j \sum_\ell \sum_n c'_{j,\ell,n} Z_{j,\ell,n} \qquad (11)$$

subject to:

single emission level per source

$$\left\{ \begin{array}{l} \sum_n Z_{j,\ell,n} = 1 \quad | \text{ for all } j,\ell \\ \\ Z_{j,\ell,n} = 1,0 \quad | \text{ for all } j,n,\ell \end{array} \right.$$

air quality constraint:

$$\sum_j \sum_n t_{i,j,\ell}\, e_{j,\ell,n} Z_{j,\ell,n} \;|$$

$$\leq S_{i,\ell} - b_{i,\ell} - f_{i,\ell} - r_{i,\ell} - p_{i,\ell} - a_{i,\ell} \;| \text{ for all } i,\ell$$

Z is a zero-one variable which is constrained to add to one for each source. Therefore, for the set of Z's for a single source and pollutant, in the solution to the linear program all Z's except one will be zero.

The emission density associated with the nonzero E is the limit for that source and pollutant. In the case of the sample point source for Baltimore discussed in Appendix D, the set of emission rates (not emission densities) and associated control costs are shown in Table 2.

The advantage of this formulation is that it allows the emission density limits to be set at specified levels that are related to certain control devices, as was not the case in the prior control cost formulation. In most contexts, we believe this is not that great an advantage and does not outweigh the higher per run cost associated with integer programming (as much as 10 times that of linear programming).

LAND VALUE (MODEL NO. 4)

The minimization of the value of additional land required to be purchased in order that the same level of economic activity be maintained is not feasible, viz.,

$$\min \sum_j \sum_k \sum_\ell c^{land}_{j,k} \; a_{j,k} \left[\frac{e^{max}_{j,k,\ell}}{E_{j,k,\ell}} - 1 \right] \qquad (12)$$

since one cannot take the reciprocal of the decision variable, E, in the objective function in an ordinary linear program.

An alternative formulation is the minimization of the cost of excess land that must be owned by a firm to comply with EDZ, viz.,

$$\text{minimize} \sum_j \sum_k \sum_\ell \sum_m \frac{c^{land}_{j,k} \; a_{j,k,m} \, e^{max}_{j,k,\ell,m} - c^{land}_{j,k} \; a_{j,k,m} \, E_{j,k,\ell,m}}{e^{max}_{j,k,\ell,m}} \qquad (13)$$

Table 7. CONTROL COST AND EMISSION SCHEDULE, EXAMPLE OF PROTOTYPICAL HEAVY INDUSTRIAL POINT SOURCE

Cost $(c_{j,n})$ dollars	Emissions $(e_{j,i,n})$ tons per year
0	6,852
6,876	5,952
13,752	5,052
20,628	4,152
22,769	3,927
24,910	3,702
27,051	3,477
39,122	3,081
51,193	2,685
63,264	2,289
75,410	1,959
87,556	1,629
99,702	1,299
122,203	1,234
135,116	939
157,617	864
170,530	579
193,031	504
205,944	219
299,791	193
393,638	166
487,485	140
581,332	113
675,179	86

Source: Derived from data in Appendix D

Equivalently, one can maximize emissions weighted by the cost of land, viz.,

$$\text{maximize} \sum_j \sum_k \sum_\ell \sum_m c^{land}_{j,k}\, a_{j,k,m}\, E_{j,k,\ell,m} \qquad (14)$$

subject to:

air quality constraint: $\sum_j \sum_k t_{i,j,k,\ell} \sum_m (E_{j,k,\ell,m}\, a_{j,k,m})$

$\le x_{i,\ell} - b_{i,\ell} - f_{i,\ell} - r_{i,\ell} - p_{i,\ell} - s_{i,\ell}$

| for all i,ℓ

attainment constraint: $E_{j,k,\ell,m} \le e^{base}_{j,k,\ell,m}$ | for all j,k,ℓ; for m = i

proximity constraint: $E_{j,k,\ell,m} - E_{j+\Delta,k,\ell,m} = 0$ | for certain Δ and j

zero cost constraint: $E_{j,k,\ell,m} \le e^{max}_{j,k,\ell,m}$ | for all j,k,ℓ,m

technological constraint: $E_{j,k,\ell,m} \ge e^{min}_{j,k,\ell,m}$ | for all j,k,ℓ,m

and perhaps the SO_x-PM feasibility constraint.

VARIANTS OF MODEL NO. 1

Variant 1A - Municipal Aggregation

The proximity constraint allows one to require the linear program to set emission density limits such that the limits in certain specified component areas (grid squares) are equal. Where this is done to a limited extent, model no. 1 is the most straightforward approach. However, one may desire to use the proximity constraint more extensively. For example, it may be desirable for emission density limits to be assigned by municipality; i.e., a municipality would be assigned one emission density limit which could then be allocated among land use categories. If there are

100 municipalities in a urban area and several component areas in each municipality, using the proximity constraint of model no. 1 becomes a cumbersome process.

An alternative approach is to define a composite transfer coefficient for the municipality. After calculating the transfer coefficients for each component area, one would determine the average transfer coefficient for each municipality, or preferably an average of the component area transfer coefficients weighted by the area of that land use in the component area. Specifically,

$$\left.\frac{\sum_{j}\sum_{k}\sum_{m} t_{i,j,k,\ell}\, a_{j,k,m}}{\sum_{j}\sum_{k}\sum_{m} a_{j,k,m}}\right| \text{ for all } i,\ell \qquad (15)$$

where the summation is taken over all component areas in the municipality and the area, $a_{j,k,m}$, is the area of the land use in that portion of the component area that is also in the municipality. Model 1 can then be used directly, where j, instead of representing a grid square index, becomes a municipality index. Note that in this variation, the proximity constraint could be redefined to allow one to set identical emission density limits in adjacent municipalities.

The use of this variant is most suited to an urban area that has many small suburban municipalities; e.g., Boston or Minneapolis-St. Paul. Even in these areas, it would be advisable to divide the core city into several sectors or to retain the component area gridding in the core city.

Variant 1B - Census Tract Component Areas

While the use of grid squares as the basic geographical unit for compiling data is well suited for the requirements of dispersion modeling, the use of a square grid is both an awkward basis for compiling the emission and land use inventories as well as for administering a set of emission density limits. If an approach such as variant 1A, municipal aggregation, is contemplated, even the accuracy of the dispersion model output is compromised when the average municipal transfer coefficient is calculated. In addition, an unwieldly data item should be necessary; viz., the amount of each grid square that is in each municipality.

An alternate approach is the use of census tracts as the component area. This allows one to compile a more accurate emission and land use inventory in less time, as well as simplifying the use of variant 1A since census tracts generally follow political boundries. The only difficulty with this approach is the question of dispersion model accuracy. We are unaware of the answer to this question. It should be noted that AQDM has been successfully run several times in this manner with the coordinates of the centroid of the census tract used as the center of a pseudo grid square.[28]

Variant 1C - Constant Emission Density Limits

The logical extrapolation of 1A would be to set one emission density limit for each land use category in the region. That is, the proximity constraint would be used for every component area. The advantages of this approach are significantly smaller linear programming costs[a] and, later, a much simpler task of administration. It will definitely allow less total emissions in the region, and therefore potentially constrain growth to a greater extent.

Though possible to simply add a proximity constraints for each grid square and land use, it is equivalent to reformulate model no. 1 without the grid square and point source index j, viz.,

$$\text{Maximize emissions} = \sum_k \sum_\ell \sum_m E_{k,\ell,m} \sum_j x_{j,k,m} \qquad (16)$$

---

[a] About 10 percent of the costs of executing model no. 1.

subject to

air quality constraint: $\sum_k \sum_m \sum_j t_{i,j,k,\ell} \; a_{j,k,m} \; g_{k,\ell,m}$

$$\le s_{i,\ell} - b_{i,\ell} - f_{i,\ell} - r_{i,\ell} - c_{i,\ell} - e_{i,\ell} \quad \text{for all } i,\ell$$

and corresponding attainment, zero cost, and technological constraints.

One problem with this approach is the definition of the upper and lower bounds. For future sources (m=2) it presents no problem. There are however, at least three options on how current sources (m=1) may be treated

1. Use the same upper and lower bounds for current sources as future sources. While this is the simplest approach, it will certainly lead to many nonconforming uses where the emission density limit for a current source is less than its present emission density. This will be especially true of large point sources.
2. Set a constant emission density limit for all area sources, as in equation (15), but treat each point source separately as in the original formulation, equation (8). This should lead to only a moderate increase in programming costs and eliminate most of the nonconforming uses.
3. Set a constant emission density limit only for future area sources. Existing area sources and point sources would be treated individually, with unique upper and lower bounds. This will eliminate all nonconforming uses, but it will only eliminate about half of the linear programming costs and cause the administration of the emission density limits to be almost as complex as the original emissions maximization, Model No. 1.

SECTION VI

GUIDELINES AND MODEL IMPLEMENTATION CONSIDERATIONS

This section first reviews emission inventory considerations and technical considerations of the linear program. Subsequently, a guide for executing an EDZ limit setting model is presented and illustrated using test city of the AQDM manual.[4]

All of the formulations of the emission density limit setting model require significant amounts of information on base year and projected design year emissions. These data must be summarized in a way that usually would not be available if the emission inventory is prepared without the requirements of emission density zoning in mind. However, if sufficient foresight is used when the emission inventory is prepared, the inventory can meet the requirements of the emission density limit setting model while incurring a negligible increment in cost.

The following considerations should be observed.

- The grid square network used for the subcounty allocation of emissions should also observe the criteria in Section II for partioning an air quality maintenance area. In practice, the grid system that one would devise using GRASE[illegible] will require only minor modification. Most of the modifications would be implemented in the absence of EDZ in the interest of accurate dispersion modeling. The exception to this would be modifications resulting from the criterion of subdividing grid squares spanning jurisdictional boundaries.

- The emission inventory must be prepared using the source classes for which emission density limits are contemplated. Most emission inventories use only three stationary area source classes; i.e., residential, commercial, and industrial; it is probable the emission density zoning regulation would utilize a more detailed classification scheme. Since the emission density limit setting model also requires the base year and planned land use of each source category in each grid square, this imposes no additional data requirements. The land use data can be conveniently used for the subcounty allocation of the emission inventory.[13]

In summary, the gridding of the AQMA must meet the additional criteria discussed in Section II, the land use and emission inventories (both current and projected) must have the same classification scheme, their geographical basis must be the gridded component areas, and the classification scheme must be the same as (or more detailed than) the categories contemplated for the administration of EDZ.

RESOURCE REQUIREMENTS

If the emission inventory is prepared with the requirements of EDZ in mind, it will require a negligible increase in resources committed to its preparation.

If one attempts to use the emission density limit setting model with a pre-existing inventory, the inventory must be modified to reflect the cited considerations. This will likely require the splitting of grid squares and a disaggregation of the emission source classes. The methods one is prone to use will probably lead to a more inaccurate inventory than if the emission inventory had originally been compiled with EDZ in mind. It will also require a moderate amount of time and resources; e.g., it required 1 man-month and an hour of computer time to modify the inventory for the Baltimore example discussed in the subsequent section. Finally, in modifying an existing inventory, care must be exercised that the resulting emission inventory is compatible with the land use inventory.

In summary, the compilation of data for input into the linear programs will be simpler and involve fewer problems if the emission inventory is developed being cognizant of the requirements of emission density zoning.

The land use inventory and plan will, in most cases, already exist. The resources required to summarize it on the geographical basis of the component areas will vary widely, depending on the form and scale of the inventory and plan. A typical situation is where the inventory is shown on a series of Prismicolor maps. One common approach is to prepare an acetate overlay of the grid system and, by planimeter or random dot grid, determine the amount of land use in each grid. It should also be noted that if the land use inventory has been summarized by census tract, consideration should be given to using the census tract as the component area.

Beside the land use inventory and the emission inventory, sufficient data must be compiled to determine the upper and lower bounds on each emission density limit. Of the three items, this can require the largest resource commitment. It is, as noted earlier, absolutely necessary and its accuracy is, in addition, critical, as many of the emission density limits may be set at either their upper or lower limits. It will require several man-months to acquire the necessary information with sufficient accuracy.

LINEAR PROGRAMMING CONSIDERATIONS

Considering the size; i.e., number of sources, of a typical air quality maintenance area, it is apparent that for all but the smallest the linear program to set emission density limits is a significant computer problem. The computer time required to solve a linear program is difficult to predict even if the time required for a similar problem is known. There are, however, several rules of thumb describing the importance of various parameters of the problem in determining solution time, viz.,

> "The most important factor is the number of ordinary function constraints. In fact, computation time tends to be roughly proportional to the cube of this number, so that doubling this number may multiply the computation time by a factor of approximately 8. By contrast, the number of variables is a relatively minor factor. Thus doubling the number of variables probably will not even double the computation time. A third factor of some importance is the density of the table of constraint coefficients (i.e., the proportion of the coefficients that are not zero) because this affects the computation time per iteration. One common rule of thumb for the number of iterations is that it tends to be roughly twice the number of functional constraints."[15]

Setting aside Model No. 3, which was not tested here, it should also be noted that the EDS problem is an atypical linear program. The matrix has a density of almost 100 percent. That is, almost every single variable — each of which is an emission density limit for a particular pollutant and source — appears with a nonzero coefficient — the transfer coefficient — in every one of the air quality constraints. (The attainment, zero cost, and technological constraints are handled as upper and lower bound statements, and are not included in the matrix. The feasibility and proximity constraints, if used, would reduce the density.) A more typical linear programming problem has a density of 10 percent to 30 percent. In other words, more variables are omitted from each constraint than are left in. General purpose linear program computer application packages, such as MPS,[18,19] are designed for the more typical problem and can be expected to be inefficient in solving a problem such as that posed by EDS.[20] A linear program code more appropriate than MPS for this type of problem could not be located. The extent of the inefficiency using MPS instead of a special purpose code could not be estimated.

With these caveats in mind, the Central Processing Unit (CPU) time and Execute Channel Program (EXCP) count required for the execution step of MPS are presented in Table 3 for several emission maximization linear programs. The information processing requirements increase

Table 1. [illegible] CHARACTERISTICS AND MPS TIMING ESTIMATES, [illegible]
[illegible] LINEAR PROGRAMMING

Application Problem characteristics	Test run of MPS on test copy of the [illegible]	County sample air quality analysis[illegible]	Sulfur oxide sample, Baltimore	Particulate matter sample, Baltimore	Sulfur oxide sample [illegible] Louisville	Particulate matter sample, Louisville[c]	Sulfur oxide sample [illegible] Louisville[c]
Machine	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rows (including object)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Columns	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Elements	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Density[a]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Iterations	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Invert ratio	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Execute step CPU time	[illegible] seconds	[illegible] seconds	[illegible] minutes	[illegible] minutes	~[illegible] minutes	~[illegible] minutes	[illegible] minutes
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	~[illegible]	~[illegible]	[illegible]
Cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[a] The input matrices were all 100 percent dense, however the introduction of a slack variable in every constraint affects the final density.

[b] Best problem solved.

[c] Infeasible solution reached.

dramatically with the size of the problem; *one who is formulating a linear program for a large air quality maintenance area should exercise caution so that the problem does not exceed the resources of the user*. If a problem is too large, one effectively has two options for simplifying it, viz., reducing the number of rows (receptors) or the number of columns (sources). (Reducing the number of feasibility or proximity constraints would have the same effect.)

To reduce the number of columns, one essentially has to (a) aggregate or remove land use categories or (b) aggregate component areas. A substantial reduction in the number of columns can only be accomplished by the former method. Some of the more homogeneous or low emission density source categories can be removed from the model. For example, the emission density limits for the residential source categories can be set *a priori* and removed as variables from the linear program. Their contribution to ambient air quality at each receptor would have to be subtracted from the standard in a manner similar to background or mobile source contributions. Alternatively, one can collapse or aggregate the land use categories. For example, the commercial and institutional categories could be combined. This is feasible either if they have approximately the same upper and lower bounds on feasible emission densities, or if component areas tend to have one or the other category of land use, or neither, but not both.

An alternative to reducing the number of columns is reducing the number of receptors. This is less preferable, because one does not know where critical receptors will be located. The sensitivity of the optimal solution to the number and location of receptors has not been completely investigated. The Louisville sulfur oxides test run was executed for two receptor sets. A different solution was reached, as discussed in Section VIII.

GUIDELINE FOR EXECUTING THE EDZ MODEL

Presented below are step-by-step instructions for preparing input for and executing an emissions maximization linear program for one pollutant using MPS. Familiarity with MPS is assumed.* Data, as described in Table 4, are assumed to have been compiled:

Table 4. REQUISITE DATA FOR PREPARING AN EMISSIONS MAXIMIZATION LINEAR PROGRAM

- Base year and design year emission inventory for all emission sources. The stationary area source emission categories must be identical to those contemplated for regulation by emission density zoning. The subcounty allocation must be done on a grid system that is compatible with the component area criteria of Section II.
- Base year land use inventory and design year land use plan that is compatible with the emission inventory in terms of grid network and subcounty allocation. The land use should be in terms of net land area, not gross land area; i.e., it should be in terms of lot area.
- Lot area and land use classification of all major point sources.
- Meteorological data, air quality, and stack height data necessary for executing AQDM for the base year and design year. This includes estimates of stack heights of future sources.
- Maximum permitted floor area ratios and minimum feasible floor area ratios (for nonindustrial development) for each land use in each component area — obtained from the land use plan, zoning ordinance, and discussions with the regional planning agency.

The guideline is divided into three sections, viz., right hand side, columns, and bounds, corresponding to discrete data elements required for the MPS input.

---

*See the Mathematical Programming System/360 Application Description Manual[19] for an overview of MPS.

Right Hand Side Section

1. Execute AQDM with the calibration option for the base year emission inventory and the air quality monitoring stations.

2. Determine the desired ambient air quality standard, in terms of an annual arithmetic mean for each receptor to be used in the EDZ model. These may be the long-term NAAQSs, a controlling long-term standard reflecting the short-term NAAQS,* or ambient air quality levels reflecting PSD or local regulations.

3. Adopt a suitable safety margin or reserve at each receptor. Subtract this from the standard. The reserve should be based, in part, on the validity of the AQDM calibration.

4. Reverse calibrate the standard at each receptor in the EDZ model; i.e., subtract the intercept from the results of step 3, then divide by the slope.

5. Execute AQDM with the source-receptor file option for the design year emission inventory.†

6. Using the source-receptor file and the design year emission inventory, calculate the contribution of each source not in the EDZ model to each receptor. Sources not in the EDZ model are those sources in the design year inventory for which emission density limits are not being set. They may include:

   - background
   - fugitive emissions
   - fugitive dust emissions
   - power plants
   - mobile sources

   Sum the contributions for each receptor.

---

*See Appendix B.

†The version of AQDM utilized in this study produces an uncalibrated source-receptor file. If the version used produces a calibrated file, Step No. 4 is not necessary. The version of AQDM utilized also produces a unit emission source receptor file. If this is not the case, the transfer coefficients must be divided by the emission rates.

7. Subtract the vector of non-EDZ source contributions (step no. 6) from the vector of reverse calibrated standards (step no. 4). The result is a column vector that is the right hand side (RHS) of the air quality constraint.

Columns Section

8. For each plant that is treated as a major source in EDZ; i.e., it remains in the source-receptor matrix, and has more than one point, develop a source-receptor contribution for each plant by averaging the individual contributions for each point within the plant weighted by the emissions from each point.

9. Reduce the source-receptor matrix by deleting each row that is a non-EDZ source. Take the transpose of this matrix. AQDM provides, for each receptor, the contribution from each source; MPS requires, for each source, the contribution at each receptor.

10. Using the land use inventory, land use plan, and point source lot area, compute the amount of each component area taken up by:

    a. current land use, by category, excluding point source land use, and

    b. planned growth in land use, by category, excluding point source land use.

11. Using the results of steps no. 9 and 10 construct a vector for each emission source; i.e., current area source, future area source, point source, that consists of:

    - the area of that source
    - the product of the area of the source and its transfer coefficient (obtained from the transposed source receptor file) to receptor no. 1
    - the product of the area of the source and its transfer coefficient to receptor no. 2
        - (and so on for each receptor)
        - (and so on for each receptor)
        - (and so on for each receptor)

- the product of the area of the source and its transfer coefficient to the i^{th} receptor.

This is the columns input to MPS; i.e., the constraint matrix.

12. Determine, as discussed in Appendix C, whether an SO_x-PM feasibility constraint is necessary. If one is required, the computed parameters are added to the end of the column vectors and RHS vector.

13. For each proximity constraint required, a 1 and -1 must be added to the ends of column vectors of the appropriate sources, and zeros must be added to the end of the column vectors of all other sources and the RHS vector.

Bounds Section

14. All necessary input to MPS has now been prepared except for the BOUNDS section; i.e., the minimum and maximum feasible values for each emission density limit. The importance of these parameters is critical; many of the emission density limits will be set at one or the other of these values. For existing sources, the lower bound is their current emission density which is computed by dividing their total annual emissions by their land area. For point sources, the lower bound is the smallest of their current emission density and their projected design year emission density excluding capacity expansion.

15. The emission density upper bound on existing sources should be defined from the AQMP projections.[1,3] Note that this is projected growth for existing sources.

16. The emission density upper bound for nonindustrial future sources is obtained by multiplying the maximum permitted floor area ratio of the land use in a specific component area and the land use based emission factor,[33] after applying existing control regulations.

17. The emission density lower bound for nonindustrial future sources is obtained by multiplying the minimum feasible floor area ratio and the most controlled land use based emission factor.

18. Upper and lower bounds for industrial future sources are obtained by considering the dirtiest and cleanest industry that can be expected to locate in each industrial land use category.

19. The data must now be formatted for input to MPS. Consult the following sections for examples of input data, MPS control programs, and sample output.

Example of Guideline

An example of the guideline is illustrated for sulfur oxides using test city of the AQDM manual[4] as a sample problem. The test city emission inventory was modified to show emission classes, as shown in Table 5. An assumed land use inventory is presented in Table 6.

1. The AQDM execution of test city, as shown on page C-9 of the AQDM manual, yields a calibration of

$$y = 0.2 + 0.5132\ x$$

2. Applying the average geometric standard deviation of 1.93, one calculates the annual mean equivalent to the short-term standard, viz.,

$$m = 80.9 = 365\ (1.93)^{0.5\ \ln 1.93 - 2.62}$$

(see equation 25). Therefore, the long-term standard, 80 $\mu g/m^3$, is controlling.

3. For the pur es of this example, no safety margin is assumed.

4. Reverse calibrating,

$$155.49 = (80 - 0.02)/0.5132$$

5. As shown in the AQDM manual.

6. Source No. 2, assumed to be a power plant, is the only non-EDE source. The product of its projected emission rate by its uncalibrated transfer coefficient (χ/Q) to each receptor yielded the second column on Table 7.

7. As shown in Table 7, the vector of non-EDE source contributions (in this case, due solely to source no. 2) is subtracted from the reverse calibrated standard, yielding the third column in Table 7, the right-hand side.

8. Of the three remaining point sources; i.e., source no. 1, 3 and 4, none have multiple emission points.

Table 5. TEST CITY BASE YEAR EMISSION INVENTORY, SO_x (tons/day)

Source no.	Light residential	Medium residential	High-rise residential	Commercial	Light industry	Heavy industry	Other
1	-	-	-	-	-	130.000	-
2	-	-	-	-	-	-	100.00
3	-	-	-	-	-	21.100	-
4	-	-	-	-	10.500	-	-
5	0.130	-	-	-	-	-	-
6	0.120	-	-	-	-	-	-
7	-	-	-	-	0.250	0.250	-
8	0.160	-	-	-	-	-	-
9	0.006	-	-	0.017	-	-	-
10	0.250	-	-	-	-	-	-
11	-	1.266	0.633	1.266	-	-	-
12	-	-	-	-	0.200	0.312	-
13	0.252	-	-	0.370	-	-	-
14	0.250	-	-	-	-	-	-
15	-	0.750	-	-	-	-	-
16	0.200	0.300	-	-	-	-	-
17	0.260	-	-	-	-	-	-
18	0.230	-	-	-	-	-	-
19	-	0.510	-	-	-	-	-
20	-	0.500	-	-	-	-	-
21	0.270	-	-	-	-	-	-

Table 6. TEST CITY LAND USE INVENTORY (square kilometers)

Table 7. CALCULATION OF THE RIGHT-HAND SIDE

Standard	Concentration due to source no. i	Right-hand side
155.49	2.58	152.9
155.49	3.08	152.4
155.49	4.28	151.2
155.49	5.58	149.9
155.49	5.58	149.9
155.49	1.78	153.7
155.49	2.18	153.3
155.49	5.88	149.6
155.49	0.98	154.5
155.49	1.58	153.9
155.49	4.18	151.3
155.49	11.18	144.3
155.49	0.88	154.6
155.49	1.18	154.3
155.49	1.58	153.9
155.49	1.58	153.9
155.49	4.08	151.4

9. The transfer coefficients from source no. 2 to each receptor are deleted from the source receptor matrix. The transpose is taken.

10. The land use inventory, Table 6, already presents the information in the required format.

11. For example, the first source has an area of 0.8094 square kilometers, and its transfer coefficients to the first two receptors are 0.1607 and 0.5067 ug/m^3 per ton/day, so the beginning of the first vector would be

- 0.8094
- 0.1301
- 0.4101

12. The SO_x-PM feasibility constraint is assumed to be unnecessary.

13. The proximity constraint is assumed to be unnecessary.

14. The lower bounds for the current sources are their current emission density. For example, the first source has a current emission rate of 130 tons per day and an area of 0.8094 square kilometers. Its lower bound would be 160.6 tons per day per square kilometer.

15. For example, based on the AQMP analysis, assume source no. 1 plans to increase its capacity by one-third. Its upper limit would therefore be 213.6 tons per day per square kilometer.

16. For example, assume the maximum permitted development density for light residential land use is 1/2 acre lots, or two dwelling units per acre. Multiplying by the appropriate land use based emission factor,[22] assume this product yields an emission density of 0.0197 tons per day per square kilometer.

17. Assume for light residential land use, the minimum expected development density is 1-1/2 acre lots. If the emission factor remains the same, the lower bound would be one-third of the upper bound calculated in step 17, or 0.00657 tons per day per square kilometer.

18. For example, assume the range of expected floor area ratios for light industrial development is 0.30 to 0.36, that light industrial sources are currently required to have a 75 percent control efficiency and the maximum feasible control efficiency is 90 percent. Also, based on an analysis of the expected industrial development, assume that the average expected emission factor is 0.0674 tons per day per square foot of floor area (638 kg/day/m^2). Therefore the upper and lower bounds would be computed as follows:

$$(0.3)\ (0.9)\ (0.0674) = 0.01821$$

$$(0.36)\ (0.75)\ (0.0674) = 0.02604$$

19. The format requirements for MPS are illustrated in Section VII.

Based on the data developed in this sample program, a MPS input data file was prepared and executed. The output of this execution is shown in Figure 3 which includes a listing of the MPS control program. The system used in this example consists of 8-digits, viz.,

Column	Index
1 - 3	Source number, sources 1 to 4 are point sources Source number, sources 5 to 21 are area sources
4 - 6	Unused, all zeros
7	Land use, 2 = light residential 3 = medium residential 4 = high rise residential 5 = commercial 6 = light industry 7 = heavy industry
8	Current or future source, 1 = current 2 = future

The interpretation of the output is explained in Section VII.

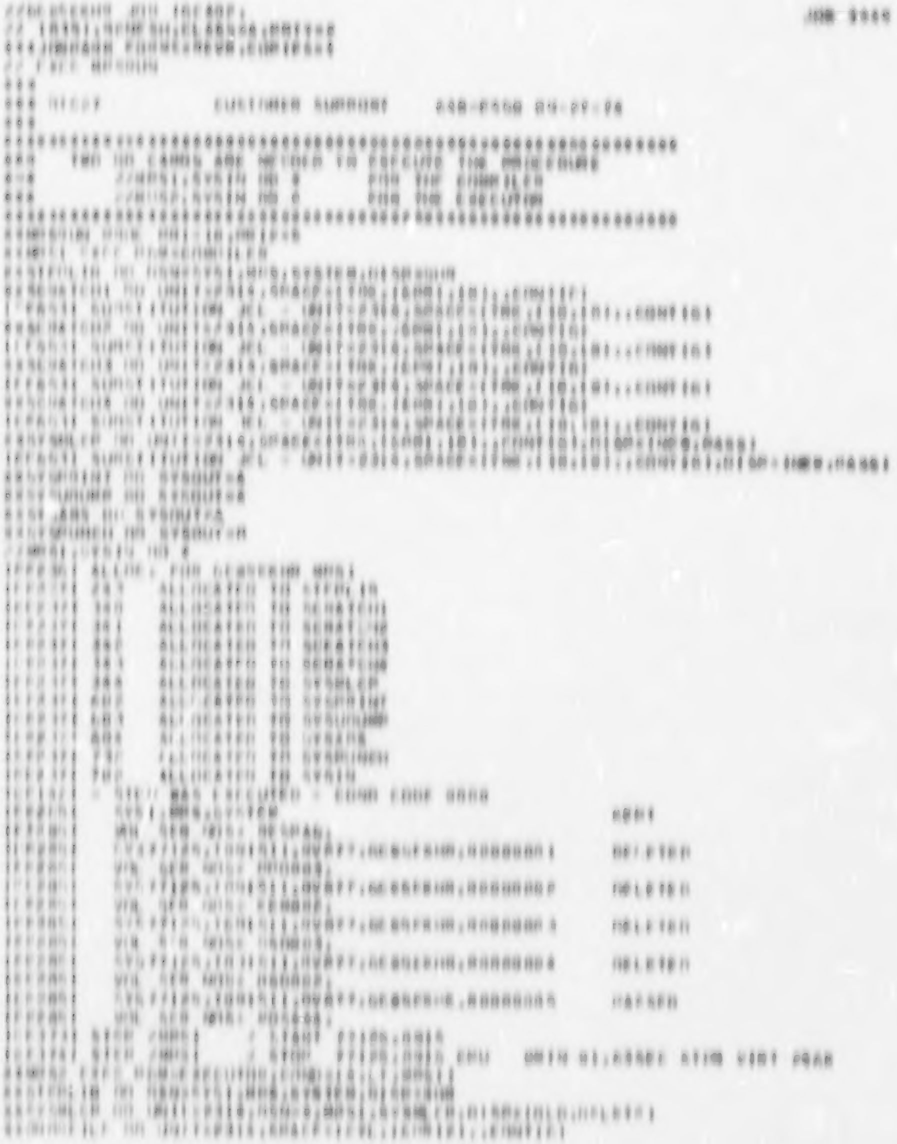


Figure 3. Test city example output

```
IEF653I SUBSTITUTION JCL - [illegible]
[illegible] DD UNIT=2314,[illegible]
IEF653I SUBSTITUTION JCL - [illegible]
[illegible] DD UNIT=2314,[illegible]
IEF653I SUBSTITUTION JCL - [illegible]
[illegible] DD UNIT=2314,[illegible]
IEF653I SUBSTITUTION JCL - [illegible]
[illegible] DD UNIT=2314,[illegible]
IEF653I SUBSTITUTION JCL - [illegible]
XXSYSPRINT DD SYSOUT=A
XXSYSUDUMP DD SYSOUT=A
XXSYSABEND DD SYSOUT=A
XXSYSPUNCH DD SYSOUT=B
//GO.SYSIN DD *
//
IEF236I ALLOC. FOR [illegible]
IEF237I 233    ALLOCATED TO STEPLIB
IEF237I [illegible]    ALLOCATED TO [illegible]
IEF237I [illegible]    ALLOCATED TO [illegible]
IEF237I [illegible]    ALLOCATED TO [illegible]
IEF237I [illegible]    ALLOCATED TO STAT
IEF237I [illegible]    ALLOCATED TO SCRATCH1
IEF237I [illegible]    ALLOCATED TO SCRATCH2
IEF237I [illegible]    ALLOCATED TO SYSPRINT
IEF237I [illegible]    ALLOCATED TO SYSUDUMP
IEF237I [illegible]    ALLOCATED TO SYSABEND
IEF237I [illegible]    ALLOCATED TO SYSPUNCH
IEF237I [illegible]    ALLOCATED TO SYSIN
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF285I   [illegible]                                        KEPT
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF285I   [illegible]                                        DELETED
IEF285I   VOL SER NOS= [illegible]
IEF373I STEP [illegible]   / START [illegible]
IEF374I STEP [illegible]   / STOP  [illegible] CPU   [illegible] STOR VIRT [illegible]
IEF375I  JOB [illegible]/ START [illegible]
IEF376I  JOB [illegible]/ STOP  [illegible] CPU   [illegible]
```

Figure 3 (continued). Test city example output

```
    CONTROL PROGRAM COMPILER - MPS/360 V2-M11

0001              PROGRAM
0002              INITIALZ
0065              MOVE(XDATA,'TESTCITY')
0066              MOVE(XPBNAME,'PBFILE')
0067              CONVERT('SUMMARY')
0068              BCDOUT
0069              SETUP('BOUND','[illegible]')
0070              MOVE(XOBJ,'[illegible]')
0071              MOVE(XRHS,'[illegible]')
0072              PRIMAL
0073              SOLUTION
0074              RANGE
0075              EXIT
0076              PEND
```

```
                EXECUTOR.    MPS/360 V2-M11
 CONVERT TESTCITY TO PBFILE
 TIME =   0.01
    SUMMARY

 1- ROWS SECTION.

   0 MINOR ERROR(S) -   0 MAJOR ERROR(S).
 2- COLUMNS SECTION.

   0 MINOR ERROR(S) -   0 MAJOR ERROR(S).
 3- RHS'S SECTION.
  [illegible]
   0 MINOR ERROR(S) -   0 MAJOR ERROR(S).
 4- BOUNDS SECTION.
  [illegible]
   0 MINOR ERROR(S) -   0 MAJOR ERROR(S).
```

Figure 3 (continued). Test city example output

Figure 3 (continued). Test city example output

```
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
```

Figure 3 (continued). Test city example output

```
                    EXECUTOR.    MPS/360 V2-M11
BCDOUT - USING PBFILE
TIME =    [illegible]


                    EXECUTOR.    MPS/360 V2-M11
NAME            TESTCITY
ROWS
 N  EMISS
 L  R001
 L  R002
 L  R003
 L  R004
 L  R005
 L  R006
 L  R007
 L  R008
 L  R009
 L  R010
 L  R011
 L  R012
 L  R013
 L  R014
 L  R015
 L  R016
 L  R017
COLUMNS
    [illegible]  EMISS      [illegible]  R001      [illegible]
    [illegible]  R002       [illegible]  R003      [illegible]
    [illegible]  R004       [illegible]  R005      [illegible]
    [illegible]  R006       [illegible]  R007      [illegible]
    [illegible]  R008       [illegible]  R009      [illegible]
    [illegible]  R010       [illegible]  R011      [illegible]
    [illegible]  R012       [illegible]  R013      [illegible]
    [illegible]  R014       [illegible]  R015      [illegible]
    [illegible]  R016       [illegible]  R017      [illegible]
    [illegible]  EMISS      [illegible]  R001      [illegible]
    [illegible]  R002       [illegible]  R003      [illegible]
    [illegible]  R004       [illegible]  R005      [illegible]
    [illegible]  R006       [illegible]  R007      [illegible]
    [illegible]  R008       [illegible]  R009      [illegible]
    [illegible]  R010       [illegible]  R011      [illegible]
    [illegible]  R012       [illegible]  R013      [illegible]
    [illegible]  R014       [illegible]  R015      [illegible]
    [illegible]  R016       [illegible]  R017      [illegible]
    [illegible]  EMISS      [illegible]  R001      [illegible]
    [illegible]  R002       [illegible]  R003      [illegible]
    [illegible]  R004       [illegible]  R005      [illegible]
    [illegible]  R006       [illegible]  R007      [illegible]
    [illegible]  R008       [illegible]  R009      [illegible]
    [illegible]  R010       [illegible]  R011      [illegible]
    [illegible]  R012       [illegible]  R013      [illegible]
    [illegible]  R014       [illegible]  R015      [illegible]
    [illegible]  R016       [illegible]  R017      [illegible]
    [illegible]  EMISS      [illegible]  R001      [illegible]
    [illegible]  R002       [illegible]  R003      [illegible]
    [illegible]  R004       [illegible]  R005      [illegible]
    [illegible]  R006       [illegible]  R007      [illegible]
    [illegible]  R008       [illegible]  R009      [illegible]
    [illegible]  R010       [illegible]  R011      [illegible]
```

Figure 3 (continued). Test city example output

Figure 3 (continued). Test city example output

Figure 3 (continued). Test city example output

Figure 3 (continued). Test city example output

```
[illegible]
```

Figure 3 (continued). Test city example output

```
[illegible]
```

Figure 3 (continued). Test city example output

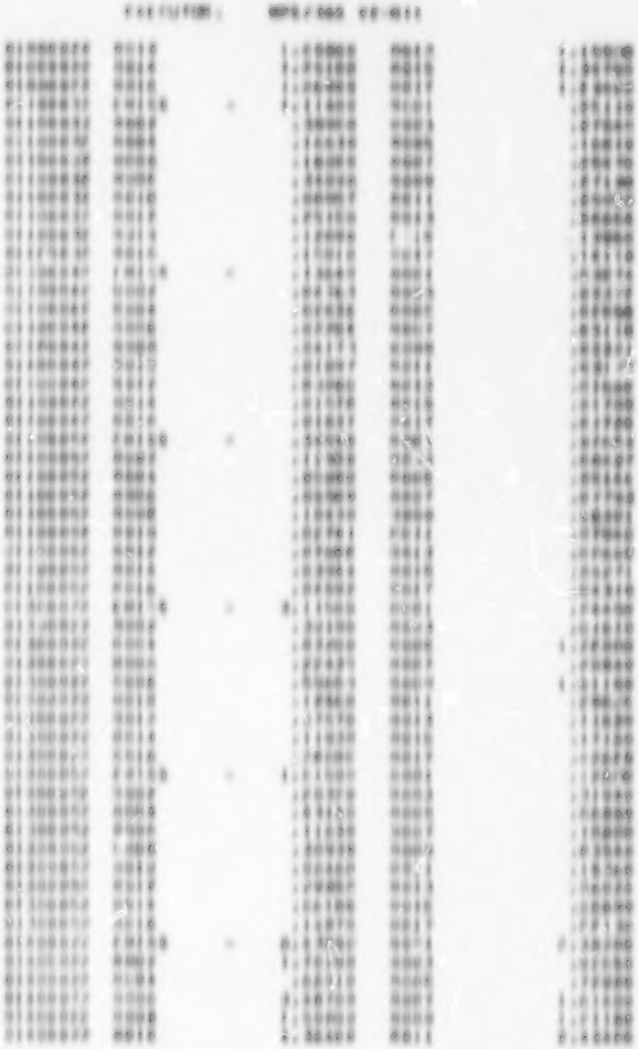


Figure 3 (continued). Test city example output

Figure 3 (continued). Test city example output

```
[illegible]
```

Figure 3 (continued). Test city example output

```
                    EXECUTOR.     MPS/360 V2-M11

 LO [illegible]     01[illegible]         .[illegible]
 UP [illegible]     01[illegible]         .[illegible]
 LO [illegible]     01[illegible]         .[illegible]
 UP [illegible]     01[illegible]         .01970
 LO [illegible]     01[illegible]         .[illegible]
 UP [illegible]     01[illegible]         .01970
 LO [illegible]     01[illegible]         .[illegible]
 UP [illegible]     01[illegible]         .01970
ENDATA


                    EXECUTOR.     MPS/360 V2-M11

SETUP  [illegible]

TIME =   0.28

   BOUND    [illegible]

 MATRIX1  ASSIGNED TO MATRIX1

 ETA1     ASSIGNED TO ETA1

 SCRATCH1 ASSIGNED TO SCRATCH1
 SCRATCH2 ASSIGNED TO SCRATCH2

 MAXIMUM PRICING NOT REQUIRED - MAXIMUM POSSIBLE   7

 NO CYCLING

     POOLS        NUMBER   SIZE    CORE
 [illegible] MAP                     92
 [illegible] REGIONS      [illegible]  [illegible]  [illegible]
 MATRIX BUFFERS   [illegible]  [illegible]  [illegible]
 ETA   BUFFERS    [illegible]  [illegible]  [illegible]

                           TOTAL  NORMAL  .FREE.  FIXED BOUNDED
 ROWS    (LOG.VAR.)         18      17      1      0      0
 COLUMNS (STR.VAR.)         69      0       0      0     69

      [illegible] ELEMENTS - [illegible] = [illegible] -    [illegible] MATRIX RECORDS (WITHOUT RHS'S)

PRIMAL       OBJ = [illegible]       RHS = [illegible]

TIME =    0.30  MINS.       PRICING    7
 SCALE =      [illegible]
 SCALE RESET TO    1.00000
 OPTIMAL SOLUTION


                    EXECUTOR.     MPS/360 V2-M11

 SOLUTION   (OPTIMAL)

 TIME =   0.31 MINS. ITERATION NUMBER =     0

          ...NAME...    ...ACTIVITY...       DEFINED AS

          FUNCTIONAL       [illegible]          [illegible]
          RESTRAINTS                         RHS
          BOUNDS....                         [illegible]
```

Figure 3 (continued). Test city example output

```
          EXECUTOR.    MPS/360 V2-M11

SECTION 1 - ROWS

 NUMBER   ...ROW..   AT   ...ACTIVITY...   SLACK ACTIVITY   ..LOWER LIMIT.   ..UPPER LIMIT.   .DUAL ACTIVITY

      1   CHISS      BS      252.15117-       252.15117             NONE             NONE           1.00000
      2   R001       BS       35.81526        116.08474             NONE        151.90000            .
      3   R002       BS       97.17264         55.22736             NONE        152.40000            .
      4   R003       BS      112.48956         38.71044             NONE        151.20000            .
      5   R004       BS       55.88729         64.03271             NONE        119.92000            .
      6   R005       BS       75.35054         75.04946             NONE        150.40000            .
      7   R006       BS       18.32189        135.37811             NONE        153.70000            .
      8   R007       BS       19.60387        133.69613             NONE        153.30000            .
      9   R008       BS       53.47604         95.12396             NONE        148.60000            .
     10   R009       BS       55.87774         90.62226             NONE        146.50000            .
     11   R010       BS       16.92212        136.97788             NONE        153.90000            .
     12   R011       BS       32.34650        118.95350             NONE        151.30000            .
     13   R012       BS       31.85886        112.44114             NONE        144.30000            .
     14   R013       BS       16.89226        137.70774             NONE        154.60000            .
     15   R014       BS       20.37511        132.92489             NONE        153.30000            .
     16   R015       BS       21.50126        132.09874             NONE        153.60000            .
     17   R016       BS       21.17537        134.12463             NONE        155.30000            .
     18   R017       BS       21.53062        129.86938             NONE        151.40000            .
```

Figure 3 (continued). Test city example output

```
          EXECUTION:   MPS/360 V2- M11

SECTION 2 - COLUMNS

 NUMBER  .COLUMN.  AT  ...ACTIVITY...  ..INPUT COST..  ..LOWER LIMIT.  ..UPPER LIMIT.  .REDUCED COST.

     19  [illegible]
     20  [illegible]
     21  [illegible]
     22  [illegible]
     23  [illegible]
     24  [illegible]
     25  [illegible]
     26  [illegible]
     27  [illegible]
     28  [illegible]
     29  [illegible]
     30  [illegible]
     31  [illegible]
     32  [illegible]
     33  [illegible]
     34  [illegible]
     35  [illegible]
     36  [illegible]
     37  [illegible]
     38  [illegible]
     39  [illegible]
     40  [illegible]
     41  [illegible]
     42  [illegible]
     43  [illegible]
     44  [illegible]
     45  [illegible]
     46  [illegible]
     47  [illegible]
     48  [illegible]
     49  [illegible]
     50  [illegible]
     51  [illegible]
     52  [illegible]
     53  [illegible]
     54  [illegible]
     55  [illegible]
     56  [illegible]
     57  [illegible]
     58  [illegible]
     59  [illegible]
     60  [illegible]
```

Figure 3 (continued). Test city example output

```
                EXECUTOR.    MPS/360 V2-M11

RANGE

TIME =    0.22 MINS.   ITERATION NUMBER =      0

        ...NAME...    ...ACTIVITY...       DEFINED AS

        FUNCTIONAL       262.15117-        [illegible]
        RESTRAINTS                         RHS
        BOUNDS....                         [illegible]
```

Figure 3 (continued). Test city example output

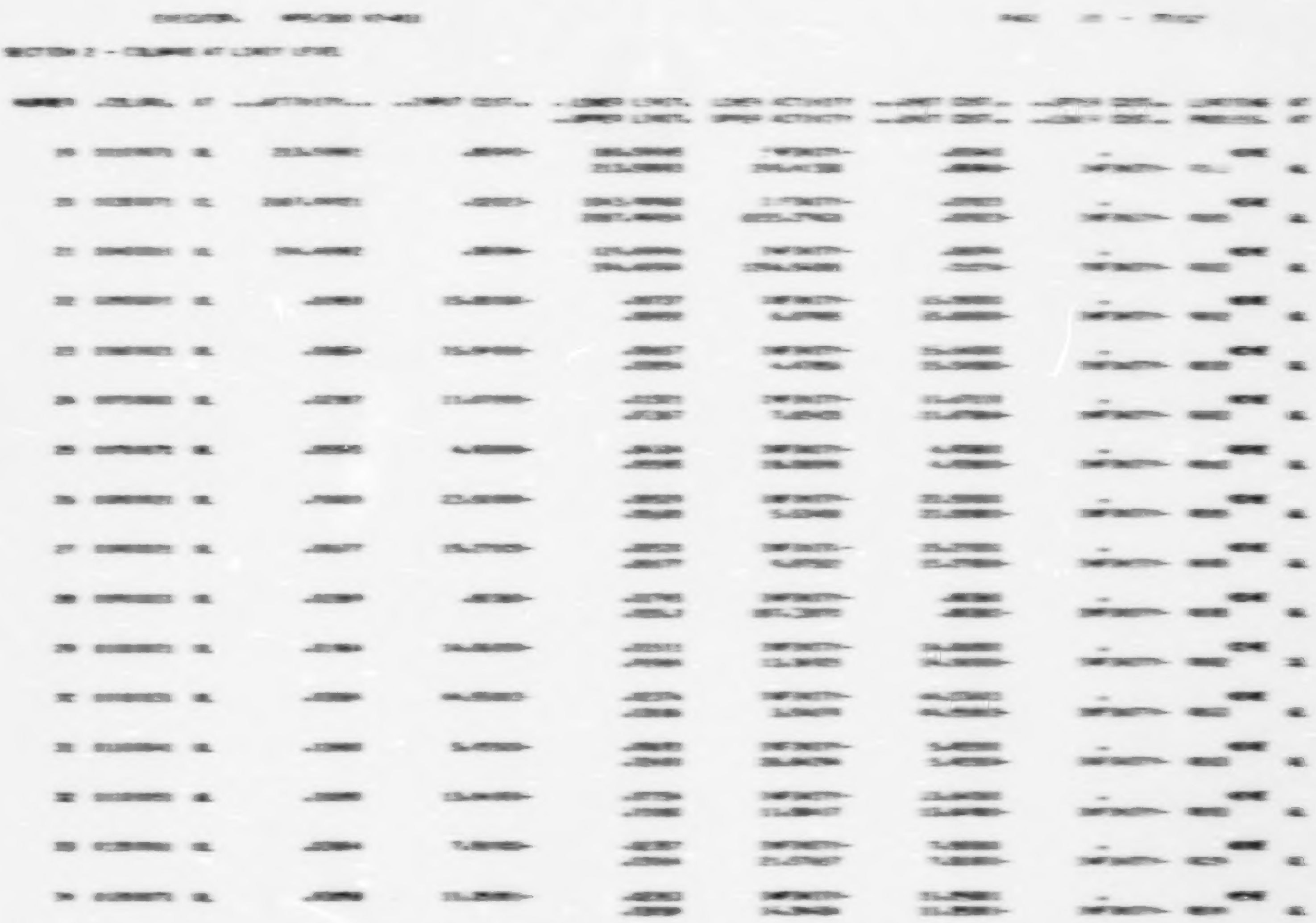


Figure 3 (continued). Test city sample output

[illegible]

Figure 3 (continued). Test city example output

```
[illegible]
```

Figure 3 (continued). Test city example output

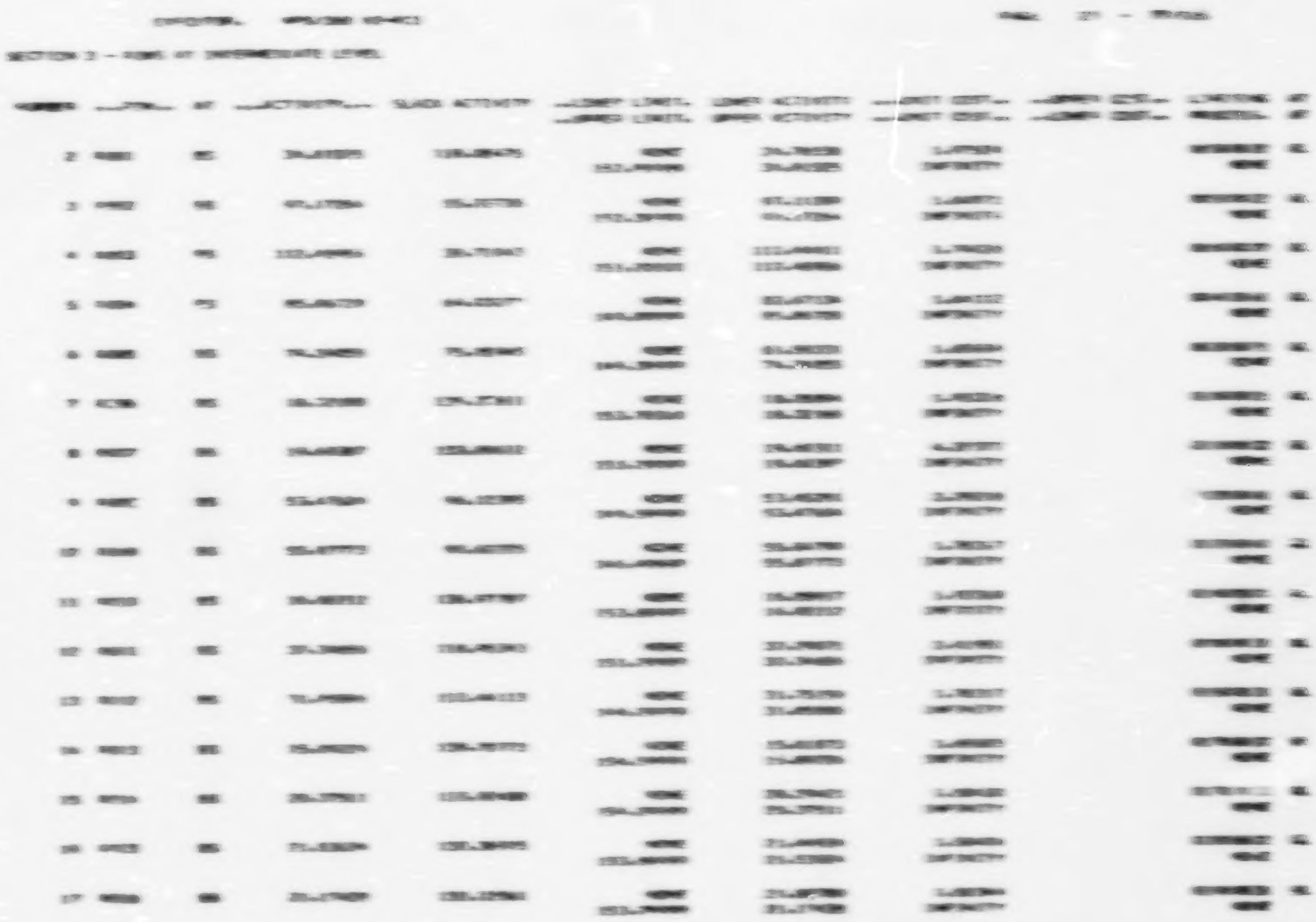


Figure 3 (continued). Test city sample output

```
[illegible]
```

Figure 3 (continued). Test city example output

SECTION VII

AN EXAMPLE OF THE EMISSIONS MAXIMIZATION FORMULATION IN THE BALTIMORE AQMA

The emission density limit setting model was executed in two AQMAs, Baltimore, Maryland and Louisville, Kentucky-Indiana. The emissions maximization formulation was executed for both pollutants in the Baltimore AQMA and the Louisville AQMA. The Baltimore example is discussed in this section; the Louisville examples are discussed in Section VIII.

DATA COMPILATION

The emission inventory and land use inventory available for the Baltimore AQMA were not compatible; in addition, neither geographic system for which the data were compiled was consistent with the component area criteria of Section II. Consequently, a new grid system was prepared. The emission inventory was reallocated to the new grid system;* the land use inventory and plan were compiled by grid square using acetate overlays.

---

*During the latter stages of the preparation of this report it was discovered that an error was made in the partitioning of industrial area source emissions in Baltimore into the light and heavy industrial land use classes. For each grid square the inventoried industrial emissions were partitioned into light and heavy industrial emissions by the light and heavy industrial land use, weighted by the mean emission densities of light and heavy industrial point sources. Through a programming error the mean plant emission densities were calculated for general commercial and light industrial rather than for light industrial and heavy industrial sources. Since the emission densities for the general commercial plants were much lower than for the light industrial plants, the heavy industrial

Point source lot areas were obtained by consulting real estate tax assessment records; estimates of floor area ratios were developed from discussions with the staff of regional and local planning agencies.

After the required data had been developed the preparation of the input proceeded as described in Section VI. A total of 2256 emission sources in 524 component areas were identified. There were seven land use categories, consistent with those specified in the regional plan and local zoning ordinances, viz:

- low density residential
- medium density residential
- high density residential
- local commercial
- general commercial
- light industrial
- heavy industrial

There was an average of 4.3 emission sources, area and point, in each component area.

All power plants and incinerators were classified as non-EDZ sources, as well as all mobile sources and the miscellaneous emission sources on NEDS area source card 5.[7] All point sources in the emission inventory that were larger than 25 tons per year were treated as point sources in the EDZ model; those less than 25 tons were assigned to the appropriate area source. A 10-meter stack height was assumed for all nonindustrial sources. Based on an examination of the point source inventory, a 65-meter height was assumed for all industrial area sources.

---

area sources were assigned a disproportionally high percentage of the total industrial area source emissions, leaving effectively a single industrial land use, namely, heavy industrial. For the Louisville simulation this error was corrected. This error does not invalidate the usefulness of the test; however, it is less representative of Baltimore and more of a similar city with a light industrial base that has a very low mean emission density.

To facilitate the manipulation of the emission and land use inventories by computer, an eight-digit identifier was constructed for each source. It consisted of the following:

digits 1-3	the component area index number
4-6	point source identification number, (zero if an area source)
7	land use category (values of 2 through 8 and corresponding to the seven land uses noted above)
8	current-future emission source identifier (1 = current, 2 = future growth)

The input to the MPS execution step consists of four discrete sets of data:[18] the ROWS section, the COLUMNS section, the RHS section, and the BOUNDS section.

The ROWS section is shown in Figure 4. The rows section is preceded by a name card with a user specified problem name. Shown is EDZBAL (emission density zoning - Baltimore). Following the name card is the rows card indicating the beginning of the ROWS section. Following that is a record for each row indicating the type of row and the user specified name of the row. The first row is the objective function, called EMISS (emissions). The N indicates it is the objective function. Subsequent records are included for each receptor. The L indicates that the constraint is a "less than or equal to" type. The name of each row is the receptor number.

The COLUMNS section, shown in Figure 5, contains, for each source, a vector consisting of first, the area of the source (the objective function parameter) and second, for each receptor, the product of the area of the source and its transfer coefficient to that receptor. Thus the first source shown in Figure 5 is the current low density residential land

```
NAME          EDZBAL
ROWS
 N  EMISS
 L  R001
 L  R002
    .
    .
    .
    .
 L  R523
 L  R524
```

Figure 4. ROWS section of SO_2 emissions maximization program

```
COLUMNS

00100021  EMISS        -0.5440E 00
00100021  R001          0.3076E 00
00100021  R002          0.2950E 00
    .
    .
    .
00100021  R524          0.1690E-01
00100032  EMISS        -0.2400E 00
00100032  R001          0.1357E 00
    .
    .
    .
    .
    .
    .
02101761  R524          0.3730E-02
03501861  EMISS        -0.1919E 02
03601861  R001          0.5622E 00
    .
    .
    .
    .
    .
```

Figure 5. COLUMNS section of SO_x emissions maximization program

use in component area 1. It has an area of 0.544 square kilometers.*
With a transfer coefficient of 0.5654 $\mu g/m^3$/ton/day, the value of the element in the matrix is 0.3076 (0.5654 x 0.5440). Since there are 524 receptors and 2256 emission sources, there are 1,184,400 ((524 + 1) × 2256) records in the COLUMNS section.

The RHS section, shown in Figure 6, contains the right-hand side constraint value (i.e., upper limit on air quality) for each row (i.e., receptor). The vector is given a user specified name, in this case, SO2.

The BOUNDS section, shown in Figure 7, contains the lower and upper bounds on emission density for each source; this vector is also given a user specified name, in this case EMISL. For example, the first source shown, source No. 12200181, has a lower limit of 0.122 and an upper limit of 2.249. The BOUNDS section contains two records for each source, or 4512 records. It is followed by an ENDATA card.

The SO_x-PM feasibility constraint was found to be unnecessary based on the analysis in Appendix C. If it had been required, it would have been added to the columns section. The proximity constraint was also not employed to simplify the testing. If used, it too would have been added to the columns section.

EXECUTION OF MPS

The problem, as compiled above, contained more matrix elements than had been expected. We had estimated that there would be fewer emission sources per component area. To reduce the problem to a more manageable size, the number of rows (i.e., receptors) was reduced. This was done

---

*The linear program actually run was a minimization. Hence the minus sign for the area, which in effect led to the minimization of the negative of emissions, equivalent to maximizing emissions.

```
RHS

SO2          R001     0.1215E+3
SO2          R002     0.1214E+3
SO2          R003     0.1213E+3
       .
       .
       .
       .
       .
SO2          R050     0.1180E+3
       .
       .
       .
       .
       .
       .
```

Figure 6. RHS section of the SO_x emissions maximization program

```
BOUNDS

LO EMISL      12200181  0.1220E+00
UP EMISL      12200181  0.2249E+01
LO EMISL      03500361  0.7936E-02
UP EMISL      03500361  0.1090E+00
                 .
                 .
                 .
                 .
                 .
UP EMISL      49400082  0.3048E+01
ENDATA
```

Figure 7. BOUNDS section of SO_x emissions maximization program

by using an option in MPS to use a subset of the constraint equations.[*] It is not recommended that this option be normally employed, for it is relatively inefficient. The number of constraint rows; i.e., receptors, was reduced to a set of 52.[†]

Because it was unnecessary to include the SOX-PM feasibility constraints, the maximization of particulate matter and sulfur oxide emissions could be solved independently. Therefore two separate linear problems could be executed, one for each pollutant.

The control program for MPS used in this example is shown in Figure 8. The CONVERT command reads the input data, converts it to binary, and stores it on a temporary disk file. In this example, it is also using a masking option to use only those rows that end in the digit five. SETUP takes certain sections of the problem and places them in a working file. CRASH is a procedure to obtain a starting point that contains fewer infeasibilities. It is an attempt at solving the linear program more efficiently. PRIMAL is the command that solves the linear program. SOLUTION outputs the optimal solution (see the example output in Figures 9 and 10) and RANGE is a postoptimal procedure that calculates how sensitive the final solution is to changes in the right-hand side of the air quality constraint and to changes in the land area of each source.

OPTIMAL SOLUTION TO SULFUR OXIDES MAXIMIZATION

After presenting information on the characteristics of the problem and an iteration log, the output of MPS presents the optimal solution to the problem and the sensitivity of the solution to changes in the parameters. The solution is described in two sections. The first is the rows

---

[*] Through the use of the masking option on the CONVERT command.

[†] The number of rows was thus 53, 52 constraints and the objective function.

```
PROGRAM
INITIALZ
MOVE(XDATA,'EDZBAL')
MOVE(XPBNAME,'PBFILE')
CONVERT('SUMMARY','RMASKS','R**5', 'EMISS',' ')
SETUP('BOUND',BJSL')
MOVE(XOBJ,'EMISS')
MOVE(XRHS,'SO2')
CRASH
PRIMAL
SOLUTION
RANGE
EXIT
PEND
```

Figure 8. MPS control program

Figure 9. [illegible] section of [illegible] optimal solution

Figure [illegible]. [illegible] section of [illegible] optimal solution sections, shown in part in Figure 9, which lists for each row an internal variable number, the row name, its status (BS indicates the row is in the basis and not binding, UL indicates the row is binding and at its upper limit), the row activity (the ambient air quality at each receptor), the slack activity, the lower and upper limits as assigned by the user, and the dual activity.* Of most interest is whether a row is at the upper limit, and the level of slack activity; i.e., unused tolerance for SO_x or the difference between the NAAQS and the projected concentration at the receptor. As can be seen in Figure 9, nine receptors are at their upper limit. The lower limit for all receptors is zero; i.e., ambient air quality is constrained to be nonnegative.

The second section of the solution output is the columns section, a portion of which is shown in Figure 10. For each column (source), the internal variable number, the column name (source index number), its status, the column activity (assigned emission density limit in units of $tons/km^2/day$), its objective function parameter (area in units of km^2), the lower and upper limits assigned by the user, and the reduced cost[*] of the associated variable. Of most interest is the activity column, which indicates the emission density limit assigned to the source.

---

*The dual activity is the value of the dual variable in the dual problem. The dual can be interpreted as minimizing the marginal value of the air quality standards used in the primal right-hand side, that is, minimizing the rate at which total emissions may be increased by increasing the standards. The value of the dual variables are sometimes called shadow prices, and can be thought of as the maximum unit price one should be willing to pay to increase the allocation of that resource; i.e., the air quality standard. The shadow prices provide a convenient ranking of the importance of each receptor. If one receptor is found to have a very high shadow price, any non-EDZ sources (e.g., power plants) that have a significant contribution to the ambient air quality at that receptor should be examined for the possibility of additional emission controls, thereby increasing the right-hand side value for the receptor. Also, if the receptor is a sensitive receptor (thus with a lower total concentration than the NAAQS), the desirability of maintaining its status should be reassessed.

Interpretation of Solution

Tables of numbers such as those shown in Figures 9 and 10 are difficult to interpret, especially in a large problem such as the one at hand. For this reason, the output of MPS was routed to a disk file. The more interesting values were retrieved and displayed graphically using SYMAP.[27] The most interesting parameter in the rows section of the solution output is the slack air quality, or the difference between the standard and projected ambient concentrations at each receptor. These values are plotted as a contour map shown in Figure 11. Immediately apparent from the figure is that all the binding receptors are grouped together in the center of the city or to the east over the Chesapeake Bay. One would suspect, therefore, that emissions would be allocated by the linear program to sources most distant (and therefore with smaller transfer coefficients) from this grouping of binding receptors. This is obvious from inspecting the spatial distribution of the emission sources that are either at their upper or lower limit, or are unconstrained; i.e., at neither limit. Figures 12 and 13 show, respectively, the status of each grid square component area for current and future light industrial sources. In both figures, those component areas on the periphery of the region tend to be binding at the upper limit while those sources at the

---

[*] The reduced cost is the rate of increase in the objective function, total emissions, per unit increase in the emission density limit. At optimality, an increase in a source currently at its upper limit will cause the total emissions to increase, an increase in a source at its lower limit will cause the total emissions to decrease, and an increase in a source in the basis will cause no change in total emissions. See the section on sensitivity analysis for more detail on these relationships.

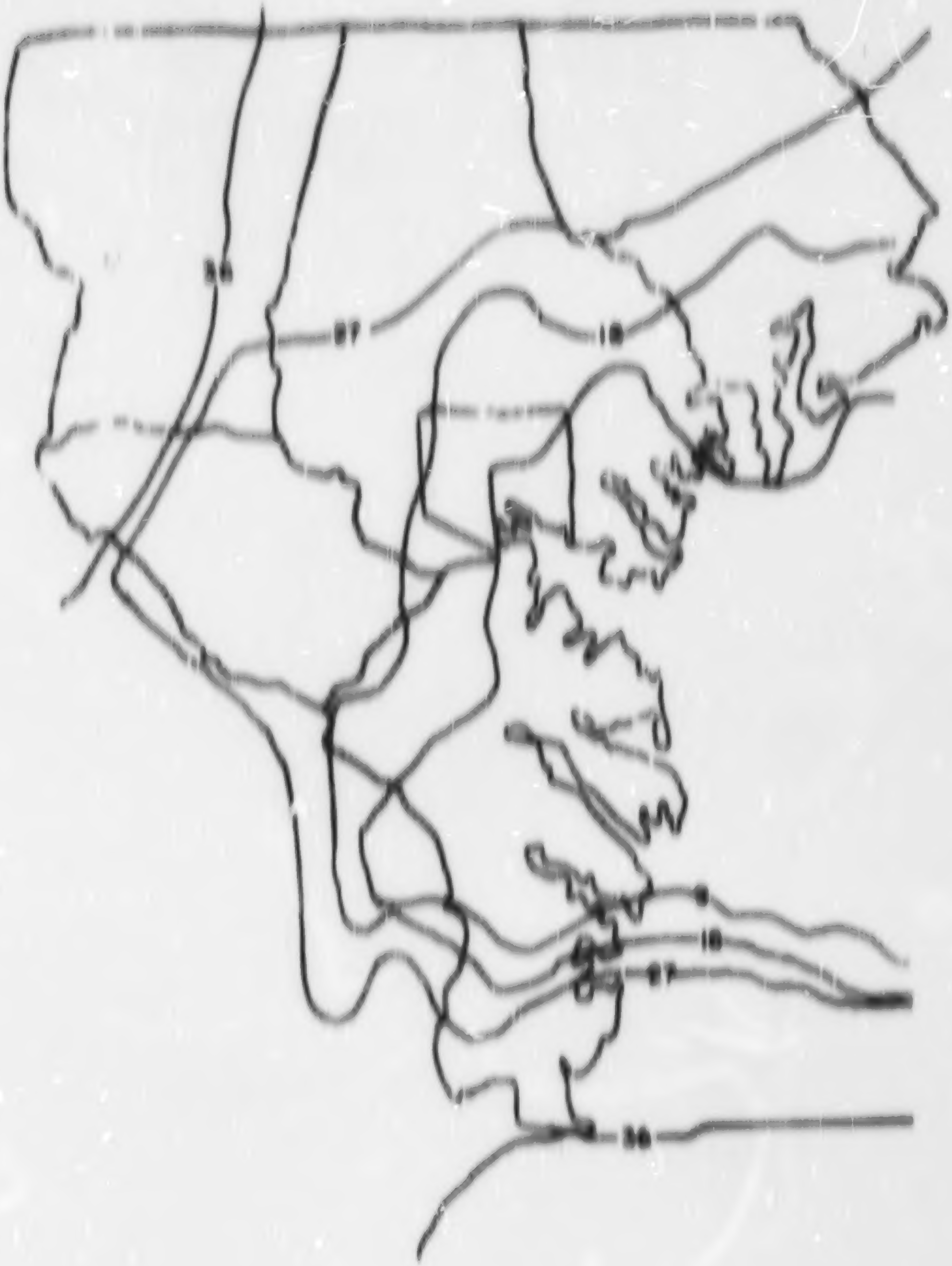

36
27
18
9
18
27
36

Figure 11. Black SO_x levels (micrograms per cubic meter)

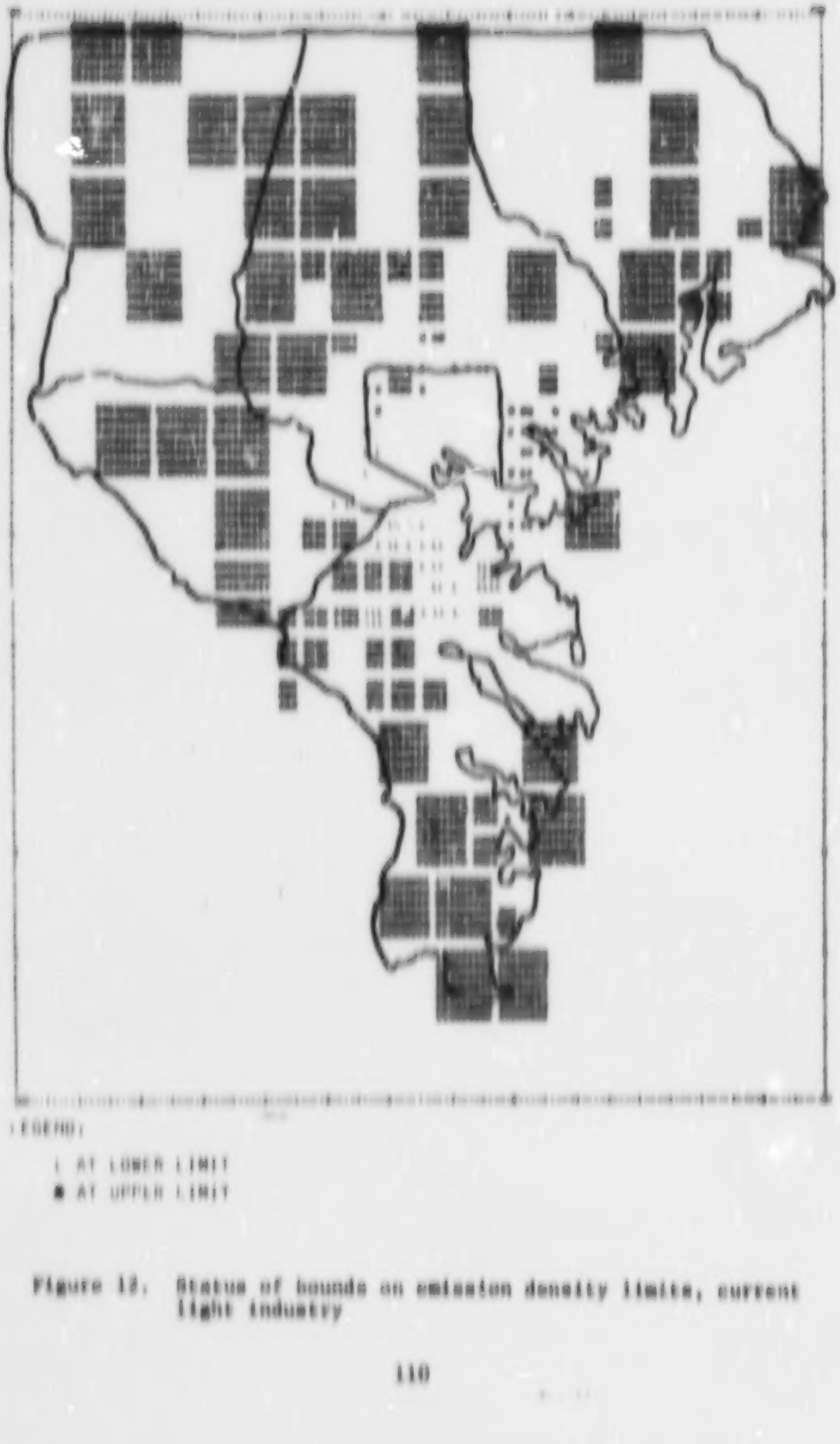

LEGEND:
I AT LOWER LIMIT
■ AT UPPER LIMIT

Figure 12. Status of bounds on emission density limits, current light industry

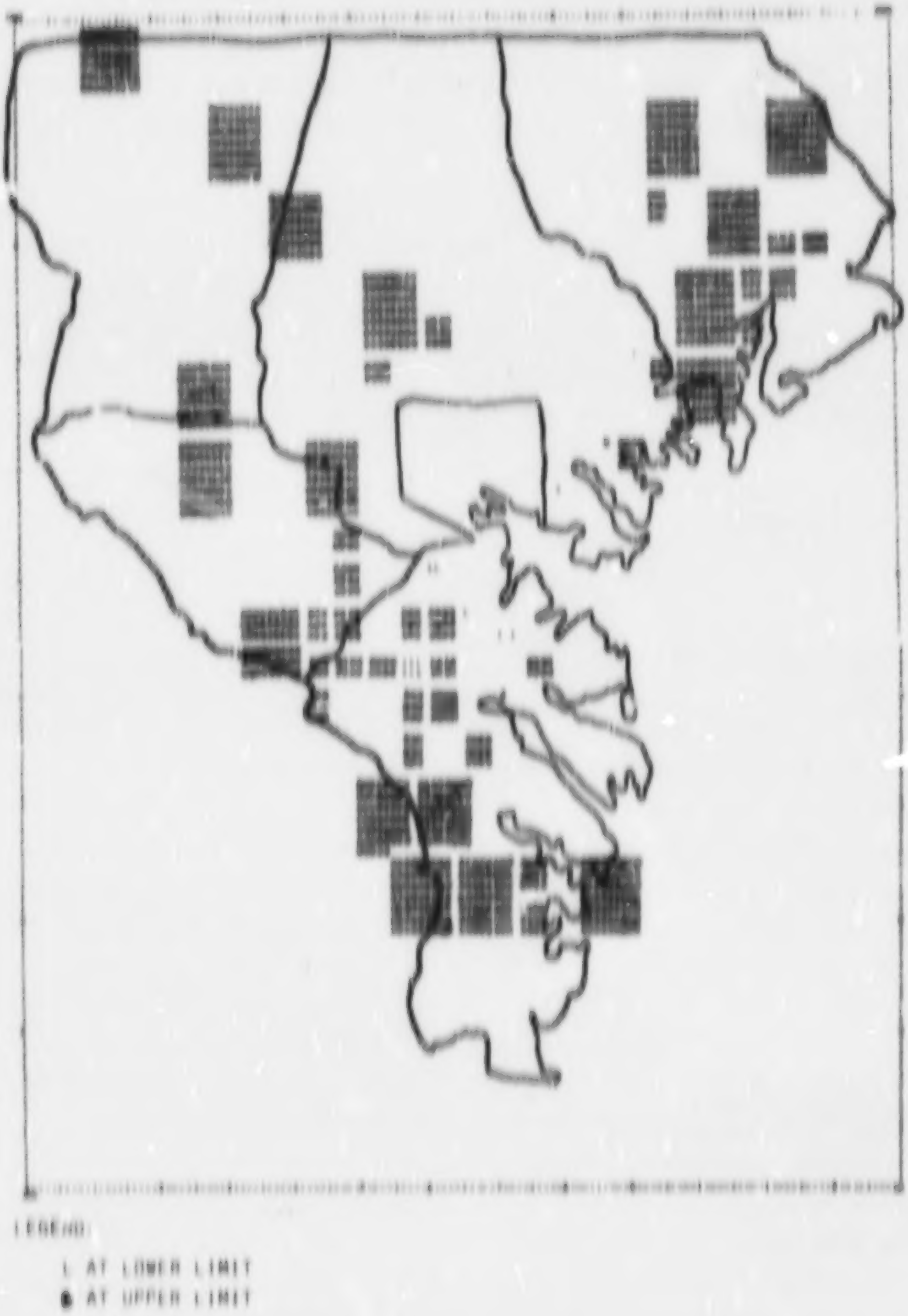

LEGEND:
L AT LOWER LIMIT
■ AT UPPER LIMIT

Figure 13. Status of bounds on emission density limits, future light industry

center of the region tend to be binding at the lower limit. The same pattern is evident in Figures 14 and 15 which show the same information for heavy industrial sources.

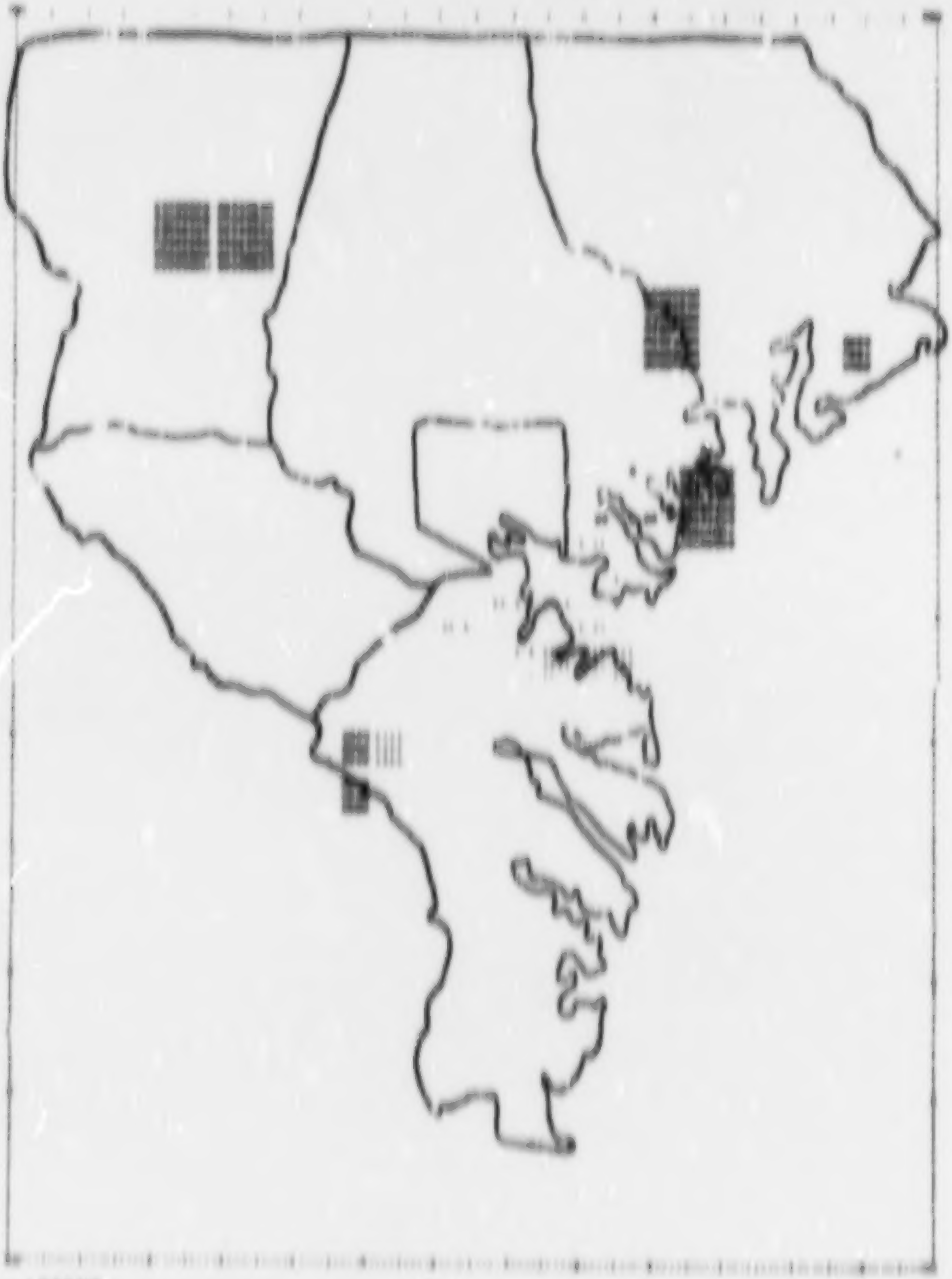
Three critical insights to the emission density maximization formulation as applied to sulfur oxides in Baltimore can be stated, viz:

- The critical (i.e., binding) receptors tend to be in the center of the region.
- The emission density limits for most sources will be set at either the upper or lower limit.
- The emission density limits for future industrial sources, which have identical bounds, will be higher on the periphery of the region. There is then a possible sprawl inducing potential inherent in simply maximizing emissions.

Sensitivity Analysis

The remainder of the output provided by MPS is a sensitivity analysis of the optimal solution. The problem is, however, so constrained that much of the analysis is of little interest. First, the maximum ambient air quality at each of the binding nine receptors can be changed only slightly (less than 0.3 $\mu g/m^3$) before the optimal solution changes; i.e., an emission source not at an upper or lower limit in the current solution reaches that limit.

The second part of the sensitivity analysis indicates how much the assigned emission density limit at binding sources can change if the land area of that source were changed. It also indicates how the value of the objective function will change. In general, the model is fairly insensitive to changes in the area of an emission source. The area of most sources could change by a factor of two or more before the emission density limit on another source is affected. The emission density limit of a source whose area is changed is greatly altered, of course.



LEGEND:

L AT LOWER LIMIT

▨ AT UPPER LIMIT

Figure 14. Status of bounds on emission density limits, current heavy industry

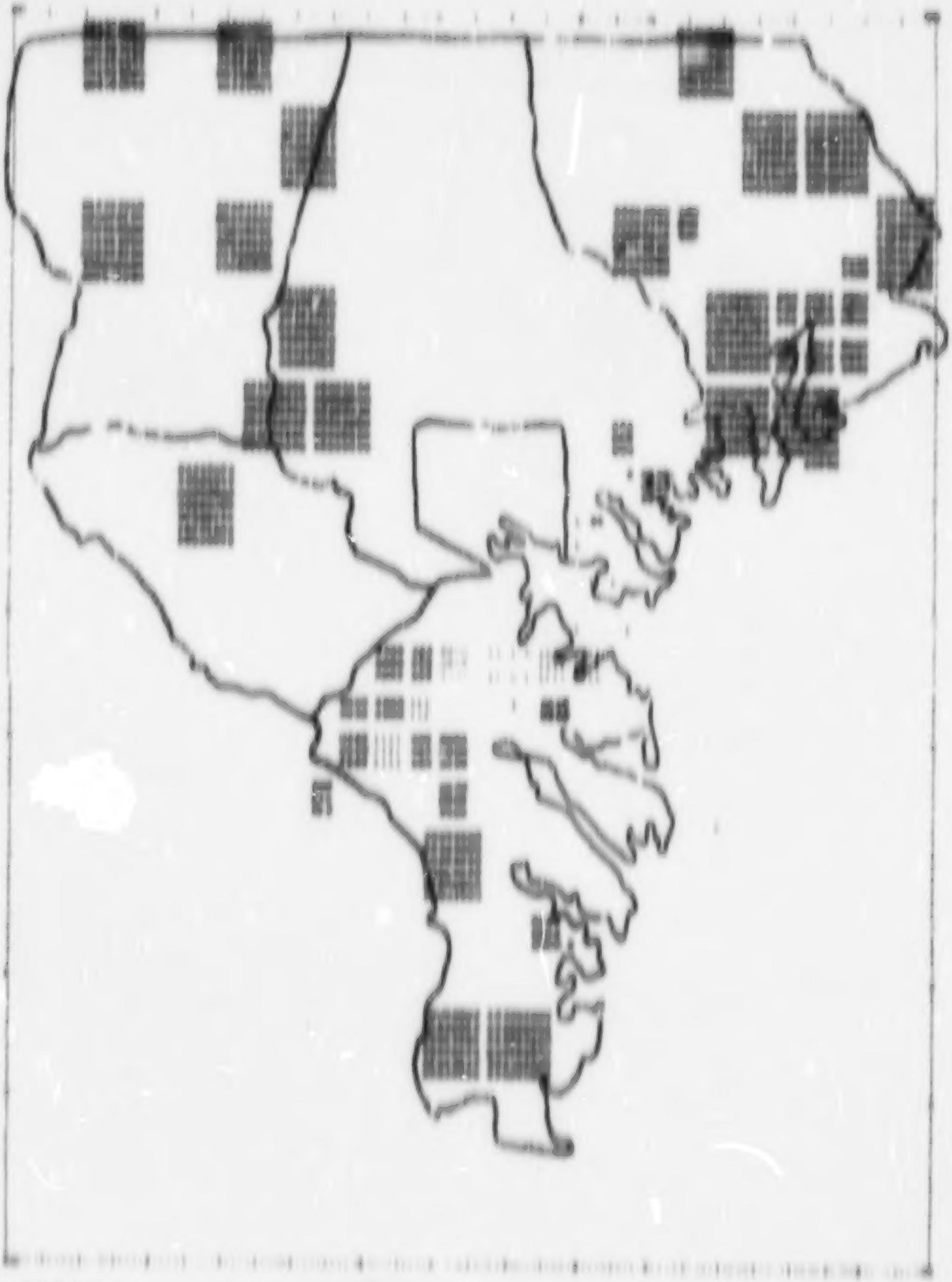

LEGEND:
L AT LOWER LIMIT
● AT UPPER LIMIT

Figure 15. Status of bounds on emission density limits, future heavy industry

The third part of the sensitivity analysis indicates how the maximum ambient air quality at unbinding receptors can change without altering the optimal solution. This analysis shows that a slight change (0.1 µg/m^3) in the ambient air quality of a nonbinding receptor will cause an emission source to reach an upper or lower limit.

The final section of the sensitivity analysis indicates how much the area of an emission source not at an upper or lower limit may change without altering the optimal solution. The emission density limit for such sources can change only slightly; i.e., less than 0.2 tons/day/km^2, before another emission source currently at its upper or lower limit is forced to change its emission rate.

PARTICULATE MATTER EXAMPLE

In a similar manner, a linear program was executed to maximize particulate matter emissions in the Baltimore AQMA. Baltimore currently is recording violations of the annual particulate NAAQS. To allow the linear program in this example to reach a feasible solution, attainment was assumed. Total suspended particulate levels were assumed to be 20 µg/m^3 less than they are in the base year.*

The optimal solution to the problem was very similar to that for the sulfur oxide example. However, in this case there was only one critical receptor, located in Baltimore City. A contour plot of slack TSP level is shown in Figure 16.

A plot of the status of the emission density limits is shown on Figure 17 for current light industry. In this example most of the sources are at their lower limits and only a few sources at the northern edge of the region are at their upper limits. In contrast with the sulfur

---

*In other words, a uniform rollback of 20 percent of the emissions at all current sources was assumed.

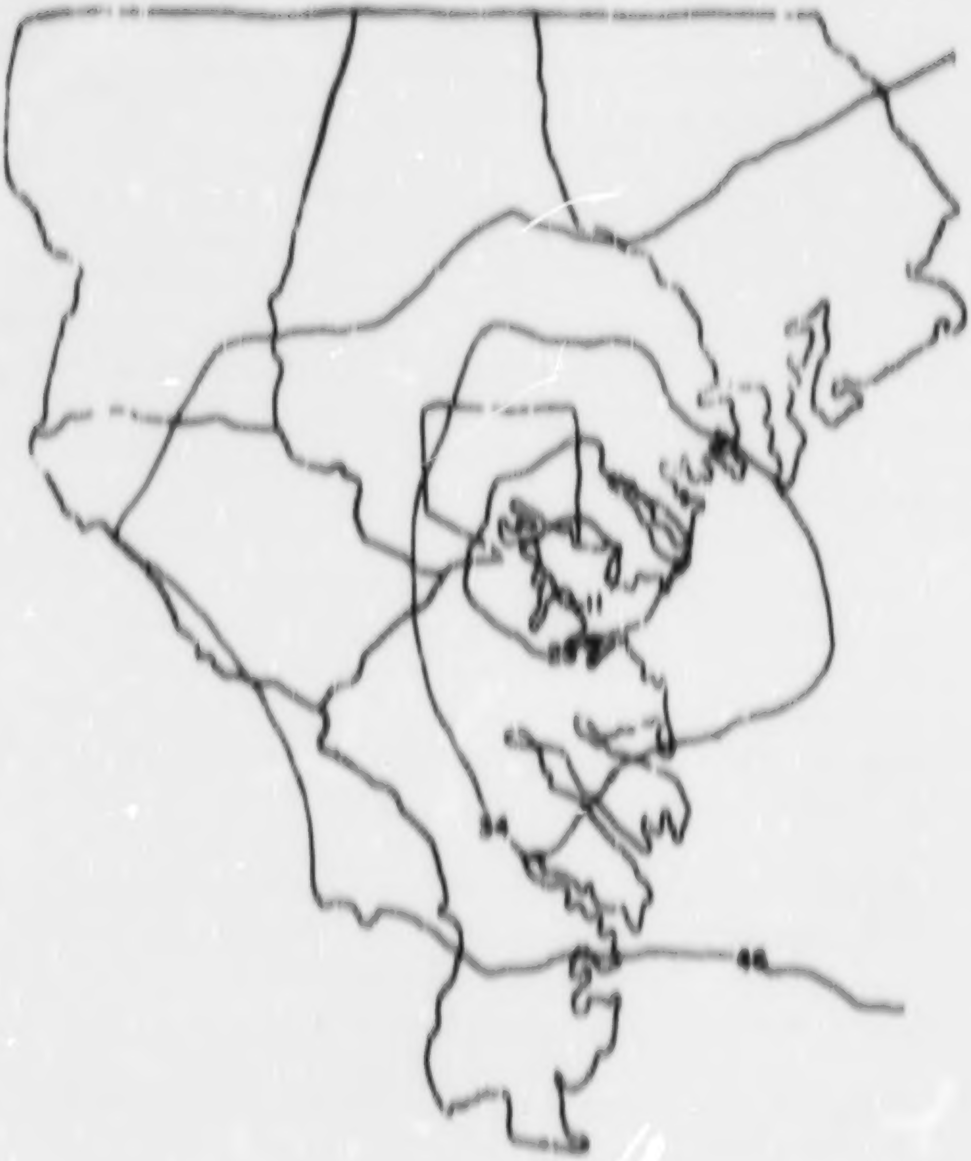
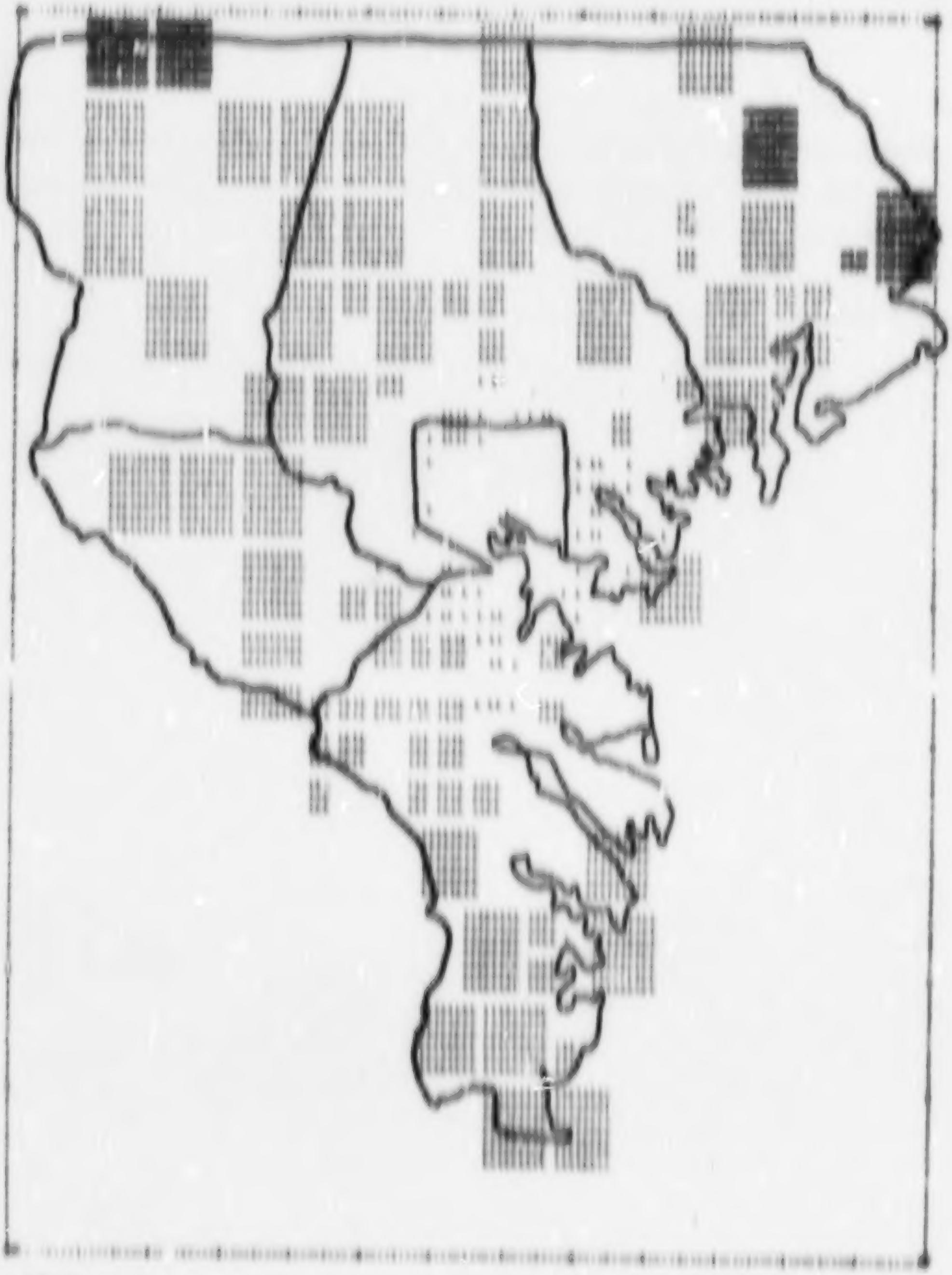


Figure 16. Stack TSP levels in Baltimore (micrograms per cubic meter)



LEGEND:

L AT LOWER LIMIT

● AT UPPER LIMIT

Figure 17. Status of bounds on emission limits, current light industry

oxide example, there was relatively less room for growth in emissions in the particulate matter example. Almost all sources had their emission limits set at the specified lower limit to allow for all the development contemplated in the land use plan. The particulate matter example does, however, support the observations made at the conclusion of the preceding interpretation section. In this case:

- There is one critical receptor at the center of the region.
- Sources at the periphery of the city tend to have their limits set at the specified upper bound and those nearer the center of the city (and the binding receptor) are set at the lower bound.

SECTION VIII

AN EXAMPLE OF THE EMISSIONS MAXIMIZATION FORMULATION IN THE LOUISVILLE AQMA

DATA COMPILATION

The emission inventory had been prepared on a census track basis. Though it would have been possible to use census tracts as component areas; to fully test the criteria of Section II it was decided to prepare a new grid system and reallocate the emission inventory to this grid system. The new grid system is shown in Figures 18 and 19.

Each county in the AQMA; i.e., Clark, Floyd, and Jefferson, had a prepared land use plan. However, the plan was presented on a different scale map in each county, respectively, 1 in. = 5000 ft, 1 in. = 500 ft, and 1 in. = 6500 ft. Clark and Floyd counties also had land use inventories compiled on colored base maps — of differing scales, 1 in. = 2000 ft, and 1 in. = 500 ft. Jefferson County's land use inventory was compiled by census tract. Jefferson County's land use inventory was reallocated to the grid square system by measuring the percentage of each census tract in a grid square. The remaining two land use inventories and the land use plans were transferred to the grid system by preparing an acetate overlay of the appropriate scale and measuring the amount of each land use category in a particular grid. This process took 2 man-months.

Point source lot areas were obtained by consulting real estate tax assessment records. This required 1 man-week.

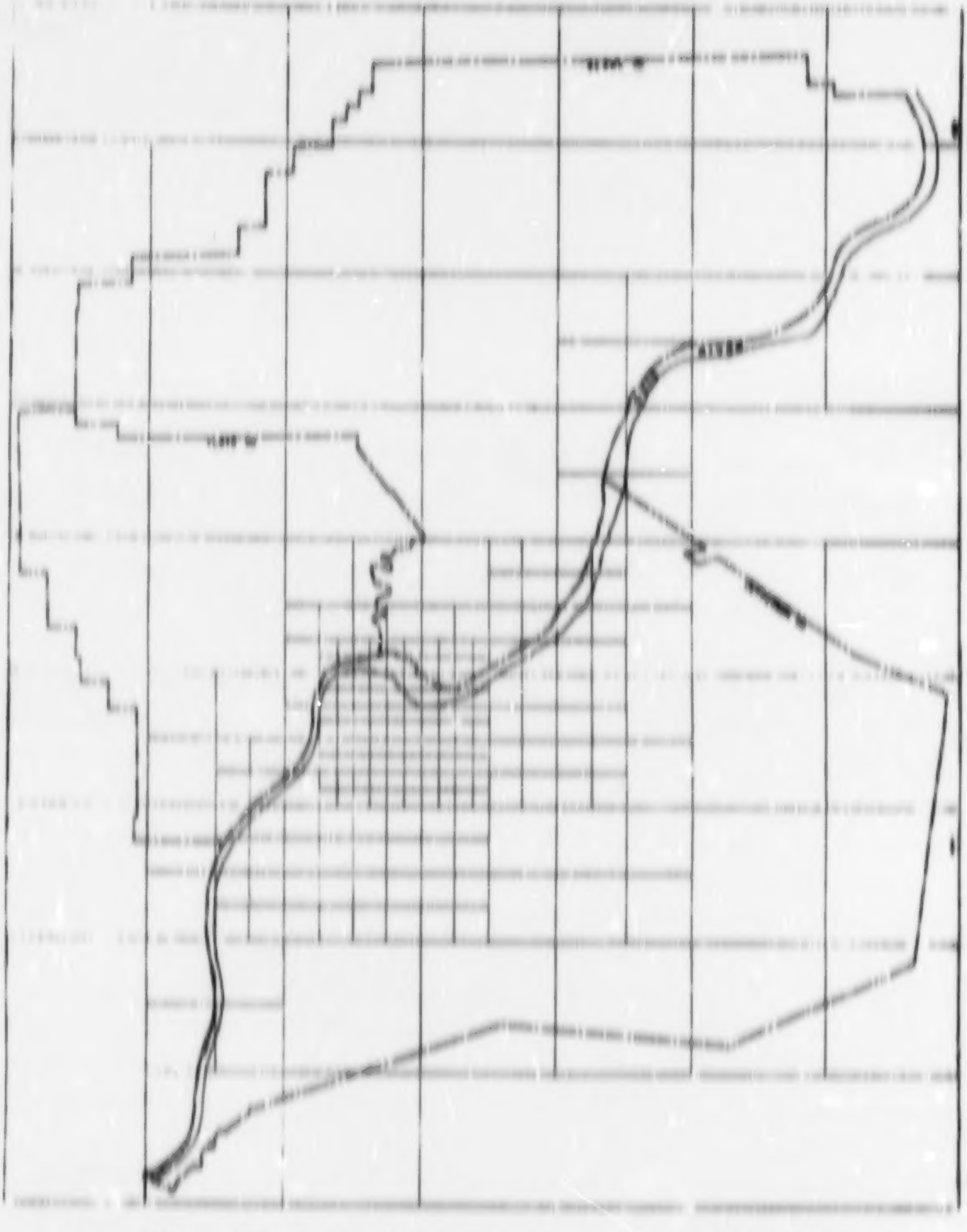


Figure 18. Louisville AQMA component area grid system

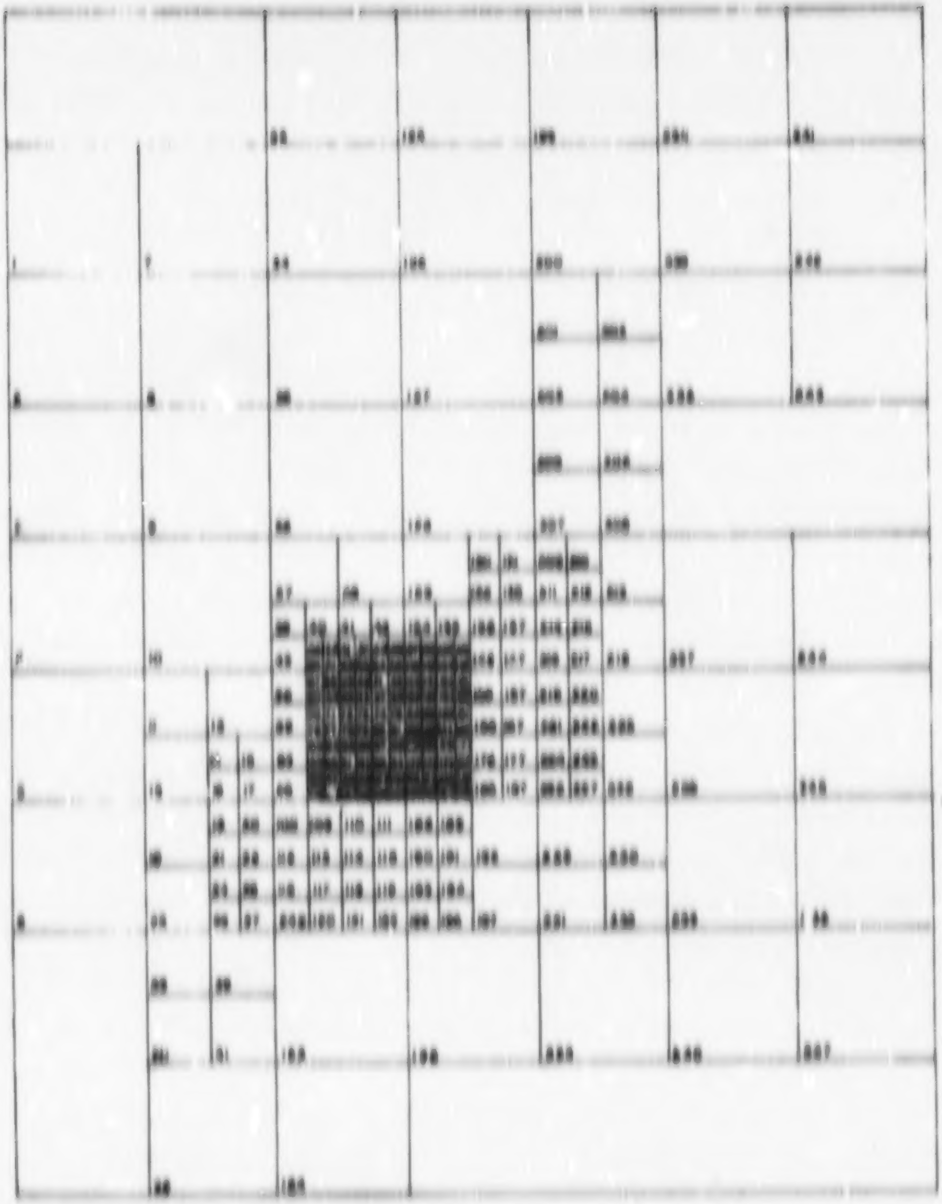


Figure 15. Numbering of Louisville AQMA component areas

To conserve resources, light and medium density residential land use was treated as a non-EDZ source, their emission density limit was established *a priori* and their projected contribution to each receptor was subtracted from the right hand side. Their emission density limits were set two geometric standard deviations larger than the geometric mean emission density of each class. The remaining land use was partioned into three categories, viz.,

- Commercial, consisting of high rise residential, commercial, office, and institutional land uses.
- Light industrial
- Heavy industrial

All power plants and incinerators were classified as non-EDZ sources, as well as all mobile sources and the miscellaneous emission sources on NEDS area source card 5.[7] All point sources in the emission inventory that were larger than 25 tons per year were treated as point sources; those less than 25 tons were assigned to the appropriate area source. The same stack heights used in Baltimore; i.e., 10 and 65 meters, were assumed.

Following these procedures, a total of 629 emission sources in 248 component areas were identified; thus, there were an average of 2.5 emission sources in each component area. This is 59 percent of the average in Baltimore and can be attributed to the deletion of the two residential classes and the aggregation of high rise residential, commercial, office and institutional into one category.

AQDM was executed to determine the calibration coefficients. However, the calibration was poor; consequently, the linear programs were executed on uncalibrated data. It is thought that the poor calibration can be attributed, at least in part, to questionable monitoring data.

The lower bound for existing sources was set at their current emission density. Point sources, whose emission density was expected to decline in the design year (1990) due to current regulations, had their lower limit set at this projected emission density (which does not include capacity expansion). The upper bound for existing sources was set at their projected 1990 emission density, based on the projected emission inventory. Sufficiently detailed floor area ratios could not be readily obtained for future nonindustrial sources. Consequently, their upper and lower bounds were determined in the same manner as future industrial sources. The upper and lower bounds for all future sources, therefore, were set by estimating the smallest and largest emission density that could be expected in each land use class. This was determined by analyzing the distribution of existing emission densities in each class, which was found to approximate a log-normal distribution. The mean was selected as the lower bound and the sum of the mean and two standard deviations was selectrd as the upper bound.

The input to the MFS execution step was identical in format to Baltimore. The feasibility and proximity constraints were also not used.

EXECUTION OF MFS

MFS was executed three times, once for particulate matter and twice for sulfur oxides. The sulfur oxide maximization was run once with 40 percent of the total receptors and once with a full compliment of receptors. The control program was similar to that illustrated in the Baltimore example.

PARTICULATE MATTER EXAMPLE

The linear program reached an infeasible solution in the particulate matter example. That is, with all sources at their lower limits, the NAAQS was still violated. Emissions at this point included the projected 1990 emissions from non-MDZ sources (power plants, mobile sources, etc.), the existing emissions from current sources, no capacity expansion at existing sources, and complete development of the vacant land according to the land use plan with a moderately stringent emission density limit. Assuming the validity of the dispersion model and the emission inventory, several options present themselves, viz.,

- Apply additional control strategies at non-EDZ sources.
- Require reductions in the emission density of existing sources covered by EDZ.
- Rerun the EDZ model with a smaller lower limit for future sources.

All three are viable strategies in the present case. Non-EDZ sources generally account for half the particulate concentration at most receptors. There are several large point sources included in the emission density limit setting model with significant contributions to receptors projected to violate the NAAQS. Finally, a more stringent lower limit on future sources could be considered.

SULFUR OXIDES EXAMPLE

Optimal Solution - 40 Percent Sample

The sulfur oxide example of the emissions maximization formulations was first run with a 40 percent random sample of total receptor set. Therefore, 102 receptors were utilized. The optimal solution to the emissions maximization had a total of 238.8 tons per day of sulfur oxide emissions. Two receptors, R083 and R087, were at their upper limit; i.e., at the NAAQS. Thirty-six sources were set at their upper limit, two at neither bound, and the remainder at their lower limit.

Interpretation of Solution - 40 Percent Sample

The slack air quality is shown in Figure 20. As was the case in Baltimore, the two binding receptors, along with four others that are close to the standard are in the core of the metropolitan region. (This is the area with the symbol '.' in Figure 20. The opposite of slack air quality is shown in Figure 21, which is the total projected sulfur oxide concentrations. It is interesting to note the contribution to ambient air quality from EDZ sources and non-EDZ sources. This is shown in Figures 22 and 23, respectively. The values represented in Figure 23 are, of course, the amount that was subtracted from the NAAQS to obtain the right-hand side.

Reviewing the pattern of emission density limits set at the upper limit, the lower limit, or unconstrained, Figures 24, 25, 26, and 27, the same pattern is discerned as was the case in Baltimore; sources at the core of the region tend to have their emission density limit set at their lower bound, those on the periphery tend to have theirs set at the upper limit. In addition, note that for some component areas, a current source is set at the upper limit while a future source of the same category is set at the lower limit. Since the transfer coefficients for two such area sources would be the same, the emission density limits could be traded off between current and future sources and still remain at the optimal solution — so long as total emissions from the component area for that land use category remained unchanged.

The emission densities in the Louisville AQMA for the base year, the design year, and the design year with all sources at their upper limit are shown in Figures 28, 29, and 30.

Sensitivity Analysis - 40 Percent Solution

As discussed in the Baltimore example, the sensitivity analysis is presented in four parts, viz., rows (receptors) at the limit level, columns (sources) at the limit level, rows at an intermediate level, and columns at an intermediate level.

The first part indicates how the optimal solution would change if the value of right-hand side were increased or decreased. For example, at the

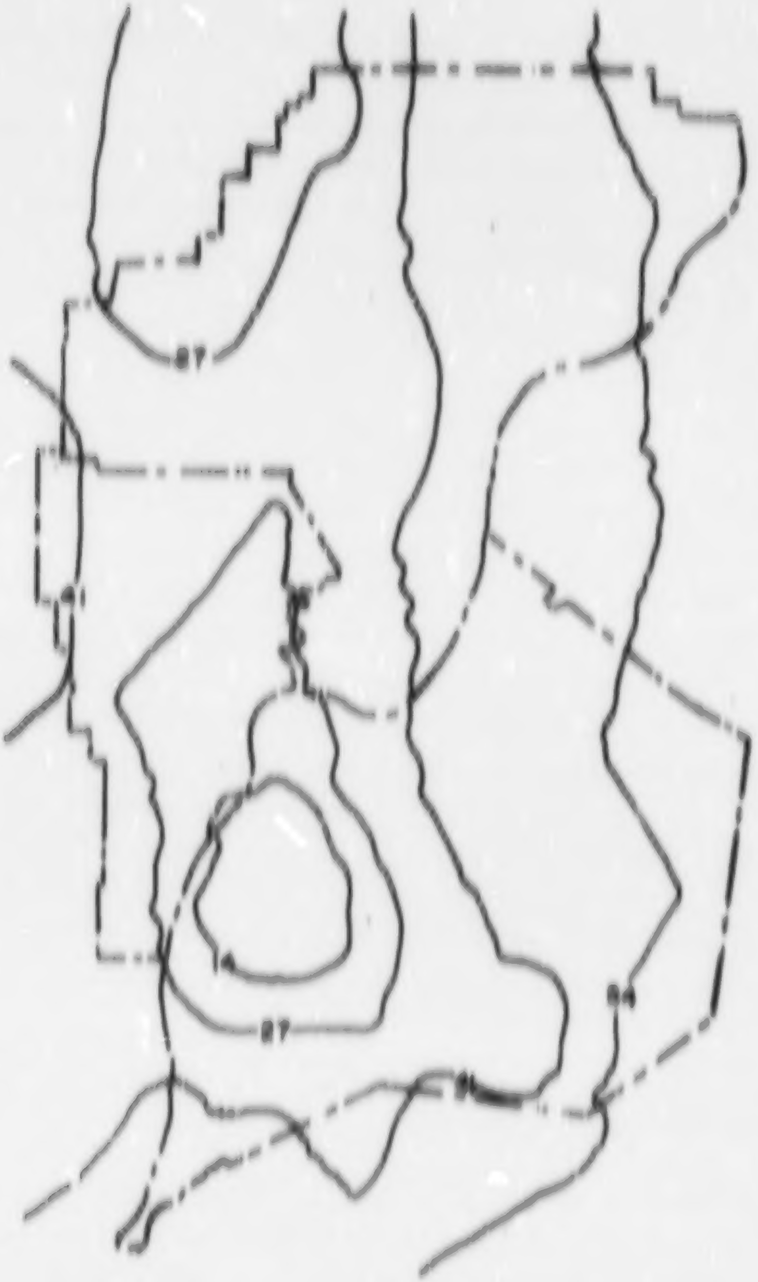

27
41
14
27
54

Figure 20. Black SO_x levels (micrograms per cubic meter)

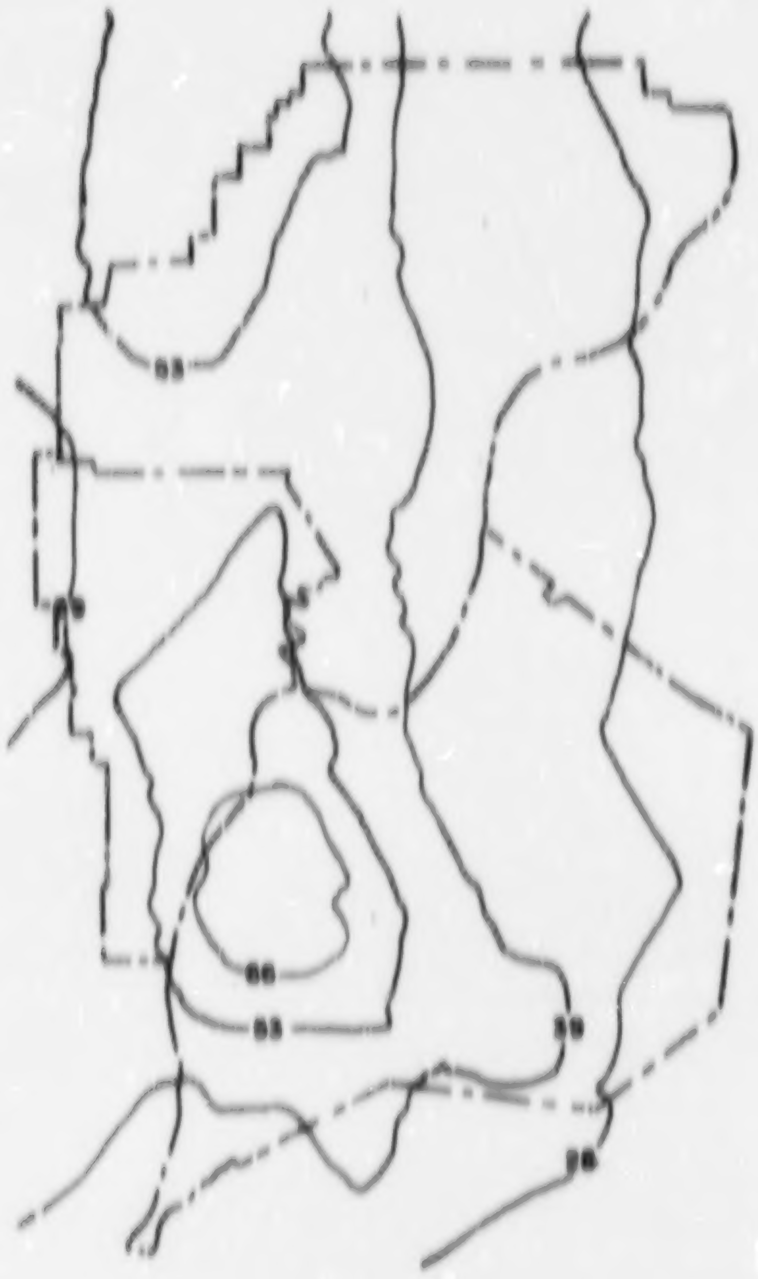

53
66
53
39
26

Figure 21. Projected SO_x concentrations (microgram per cubic meter)

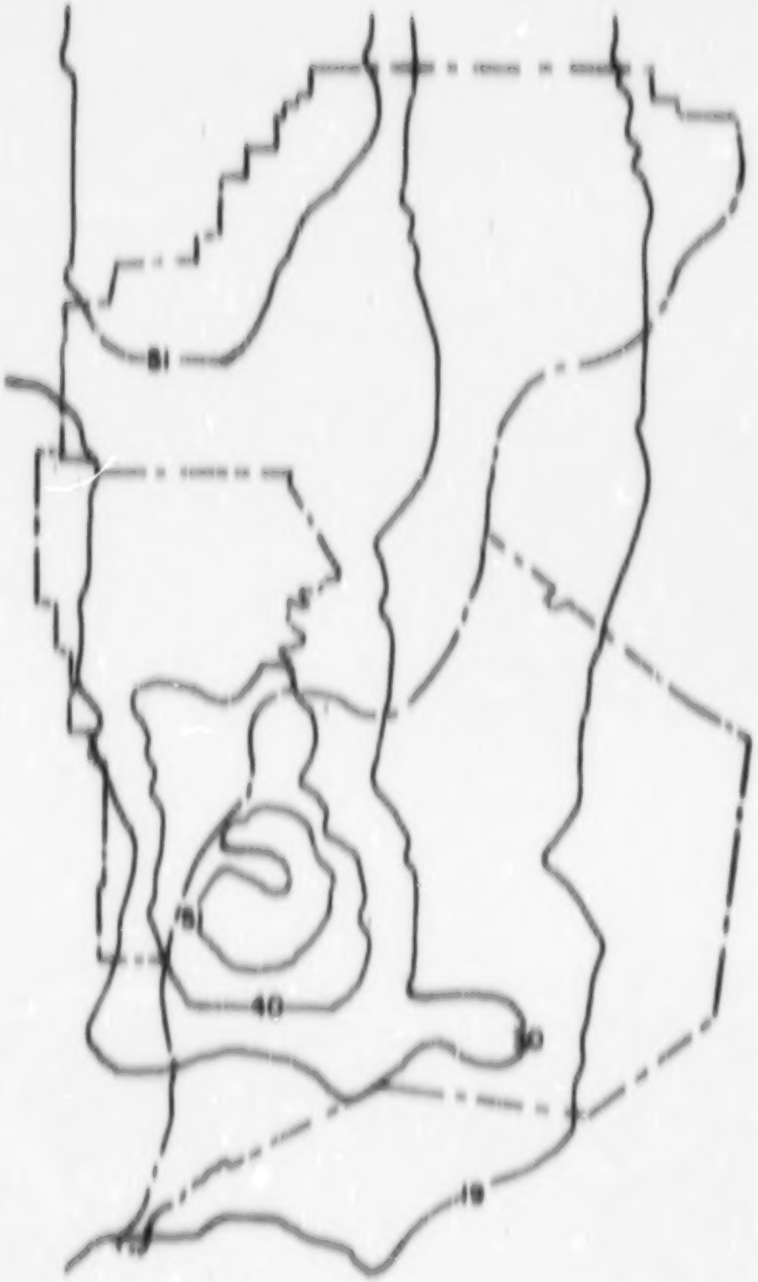

81
75
40
30
19

Figure 22. SO$_x$ levels attributed to EDZ sources
(micrograms per cubic meter)

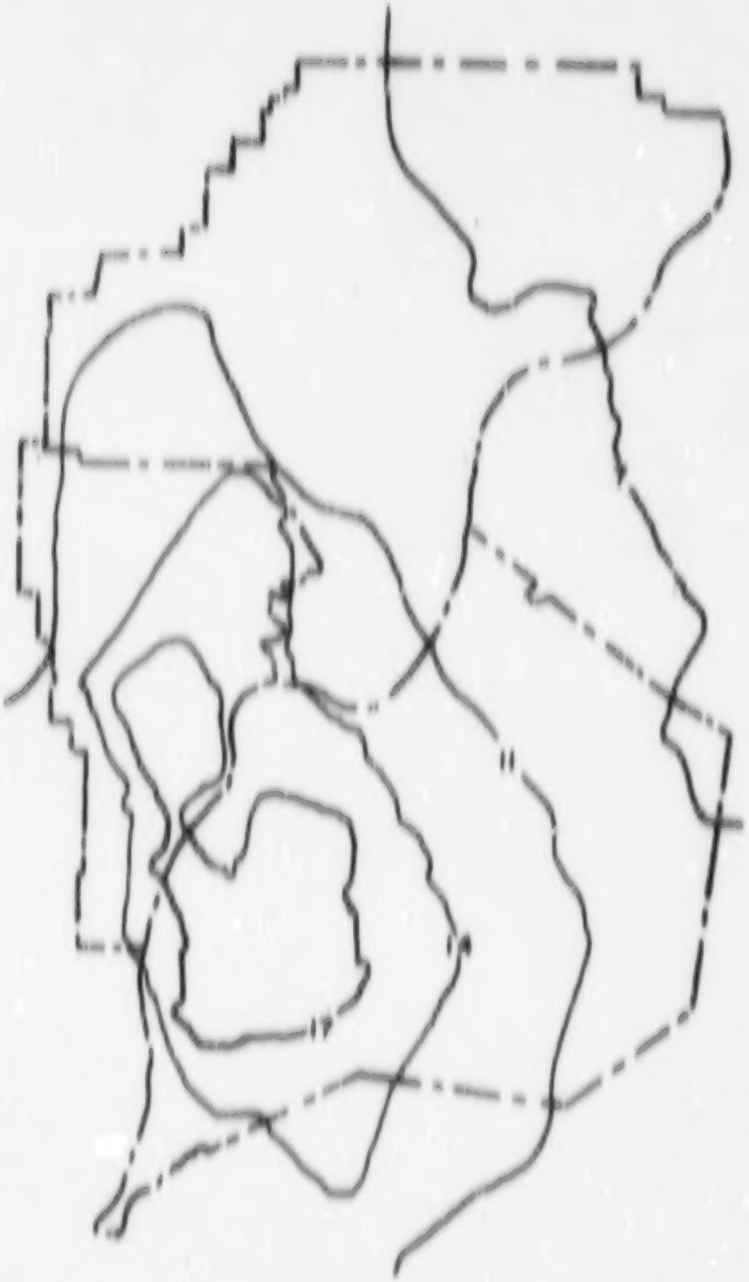


Figure 23. SO_2 levels attributed to non-EDZ sources (micrograms per cubic meter)

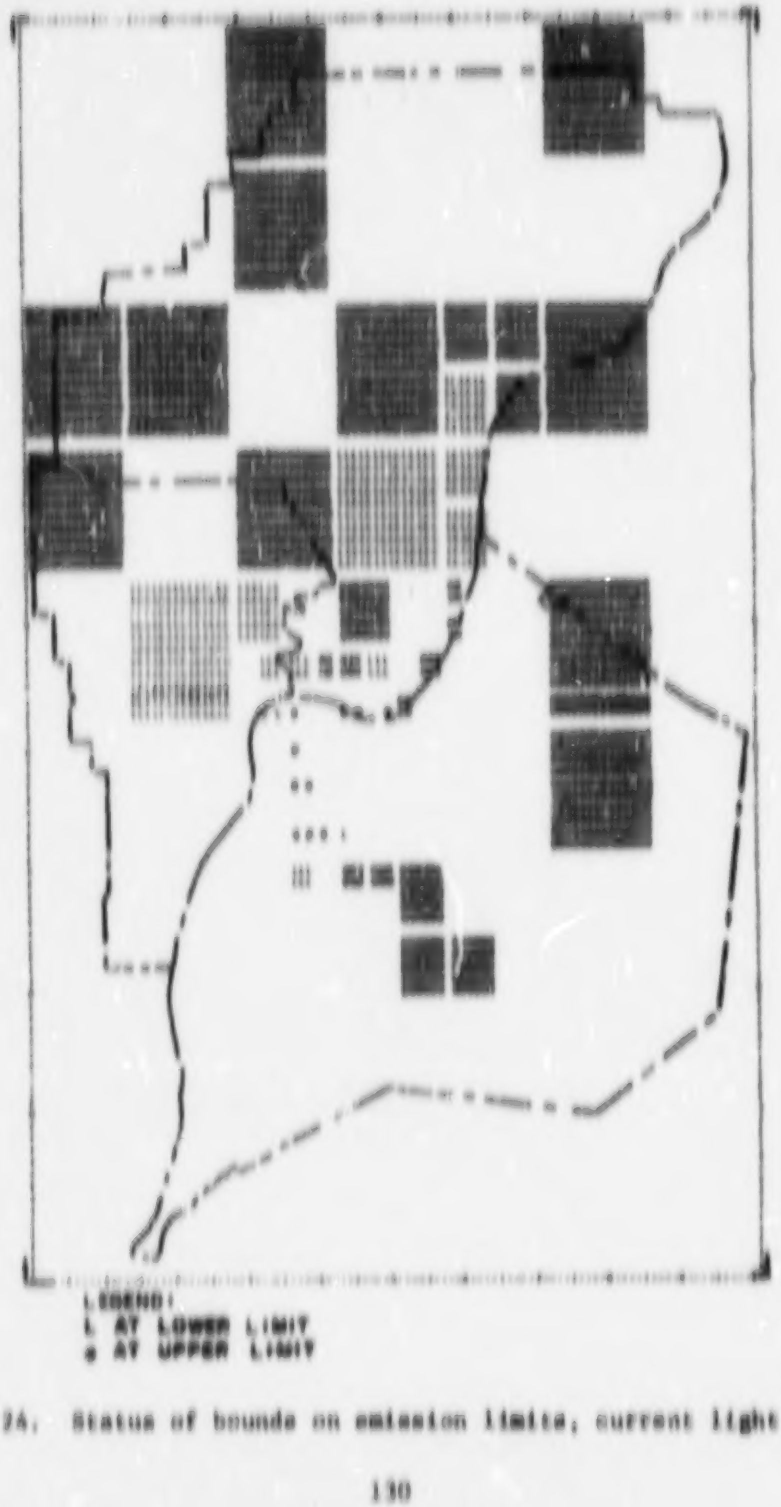

LEGEND:
L AT LOWER LIMIT
# AT UPPER LIMIT

Figure 24. Status of bounds on emission limits, current light industry

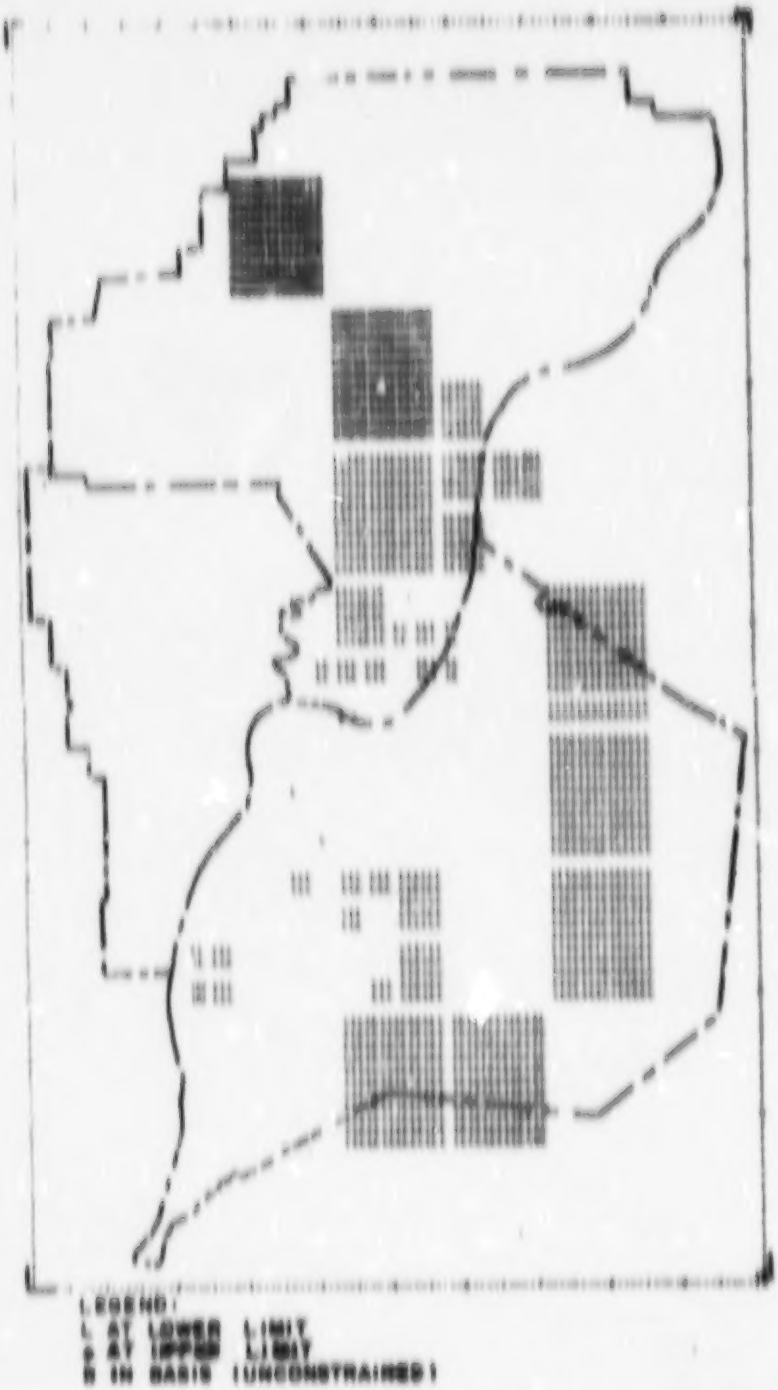

LEGEND:
L AT LOWER LIMIT
* AT UPPER LIMIT
B IN BASIS (UNCONSTRAINED)

Figure 25. Status of bounds on emission limits, future light industry

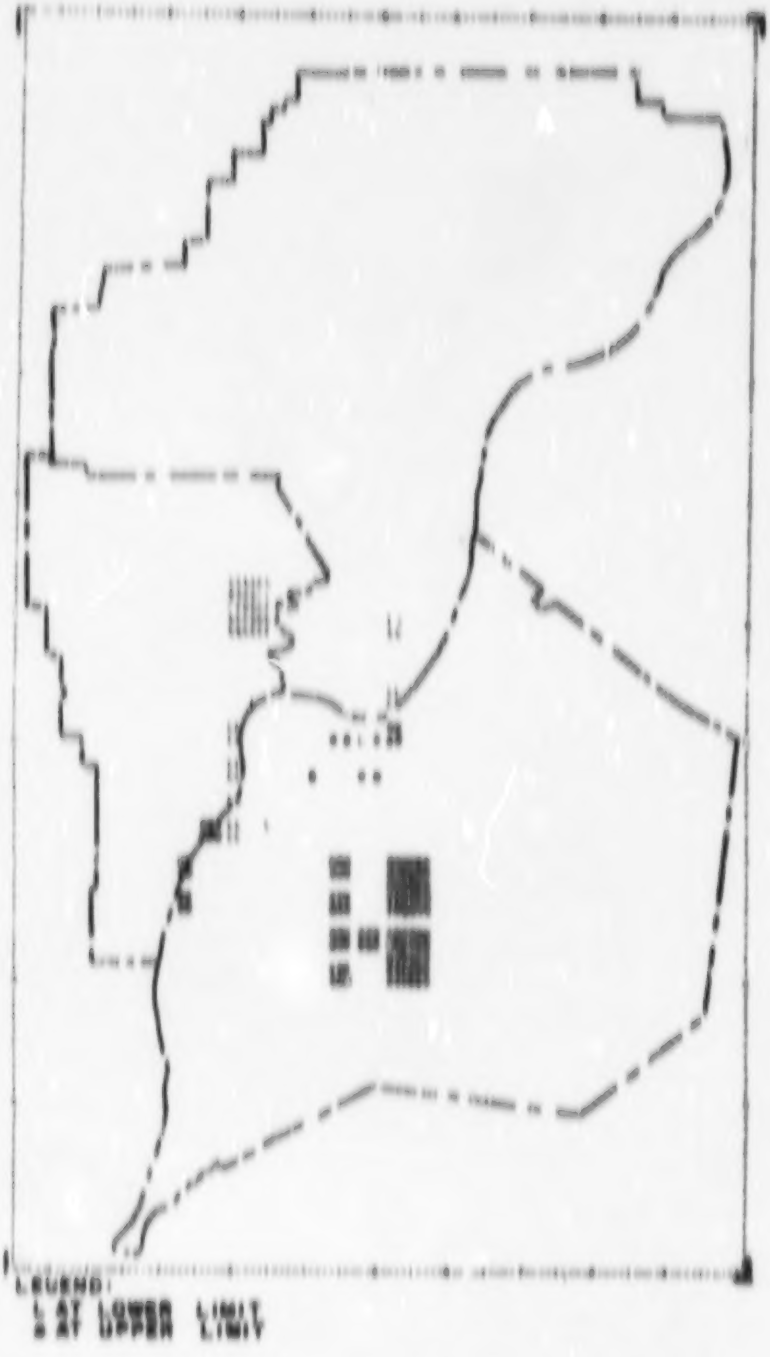

LEGEND:
L AT LOWER LIMIT
U AT UPPER LIMIT

Figure 26. Status of bounds on emission limits, current heavy industry

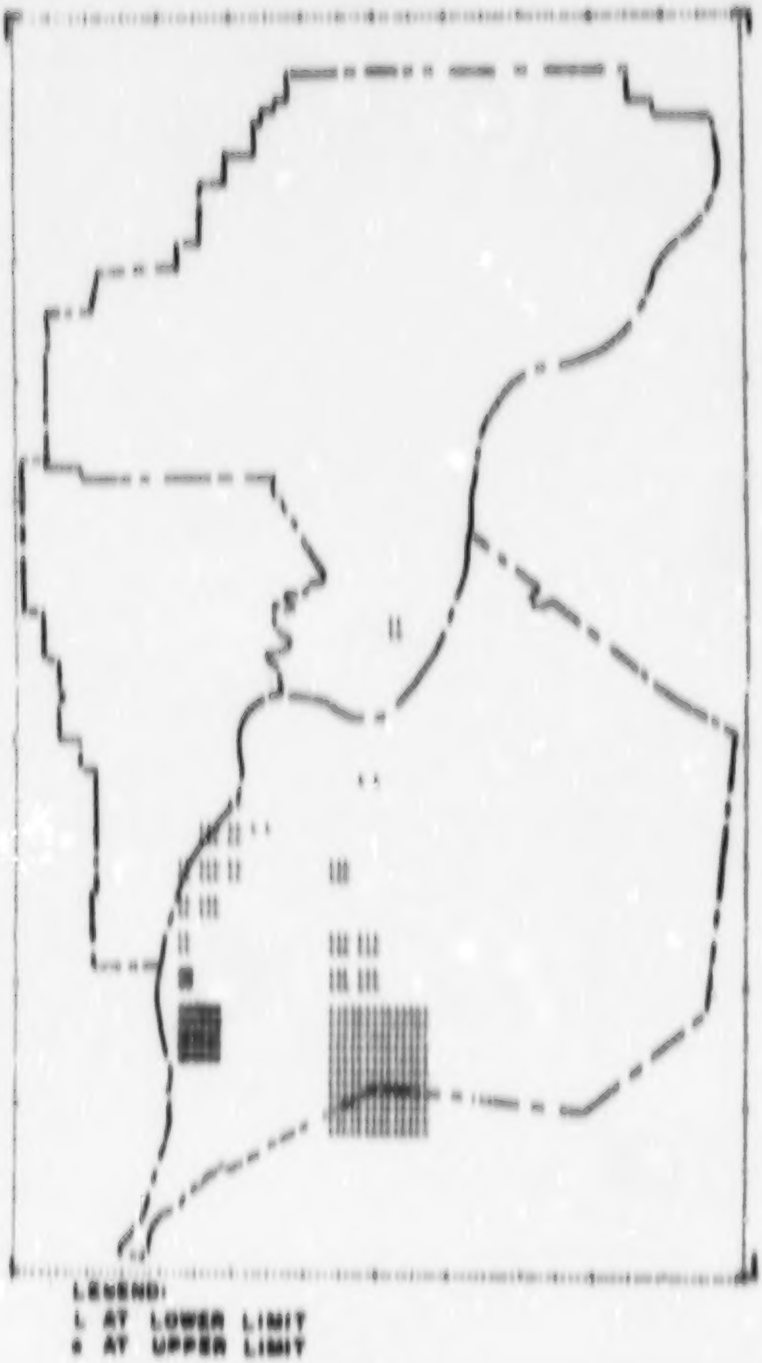
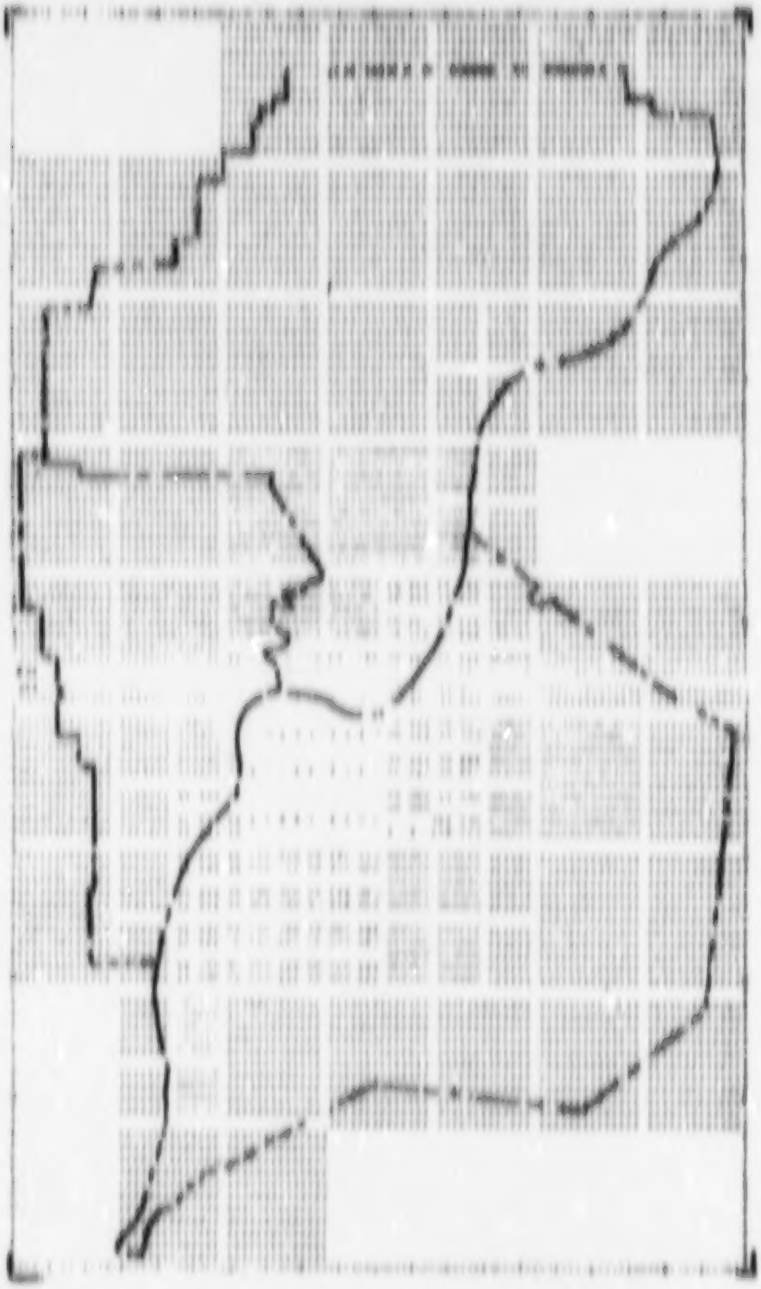
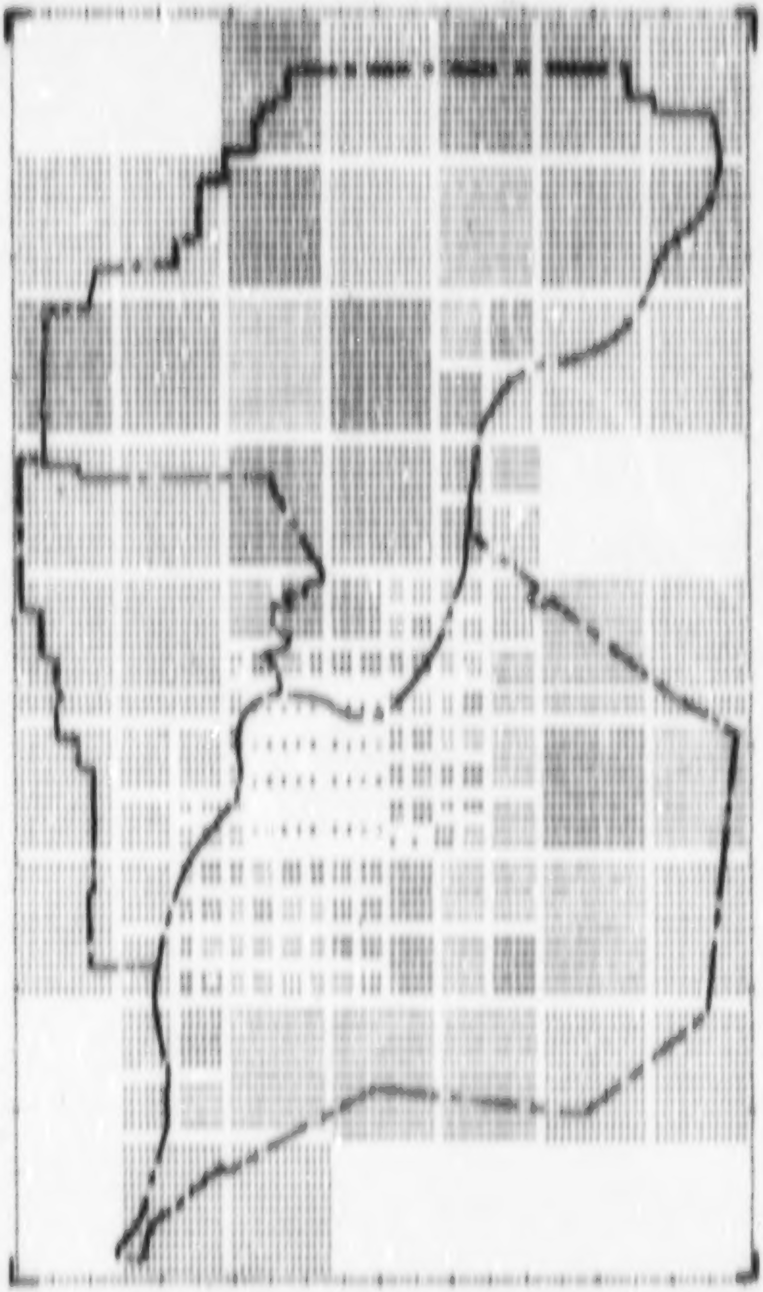

LEGEND:
L AT LOWER LIMIT
+ AT UPPER LIMIT

Figure 27. Status of bounds on emission limits, future heavy industry



	░	▒	▓	█
MINIMUM	.00000	.00088	.00584	.02770
MAXIMUM	.00088	.00584	.02770	.27702

Figure 28. SO$_x$ emission density, base year (tons year day per square kilometer)



	░	▒	▓	▦	█
MINIMUM	.00000	.00085	.00884	.02770	.27702
MAXIMUM	.00085	.00884	.02770	.27702	.83186

Figure 29. SO_2 emission density, design year (tons per day per square kilometer)

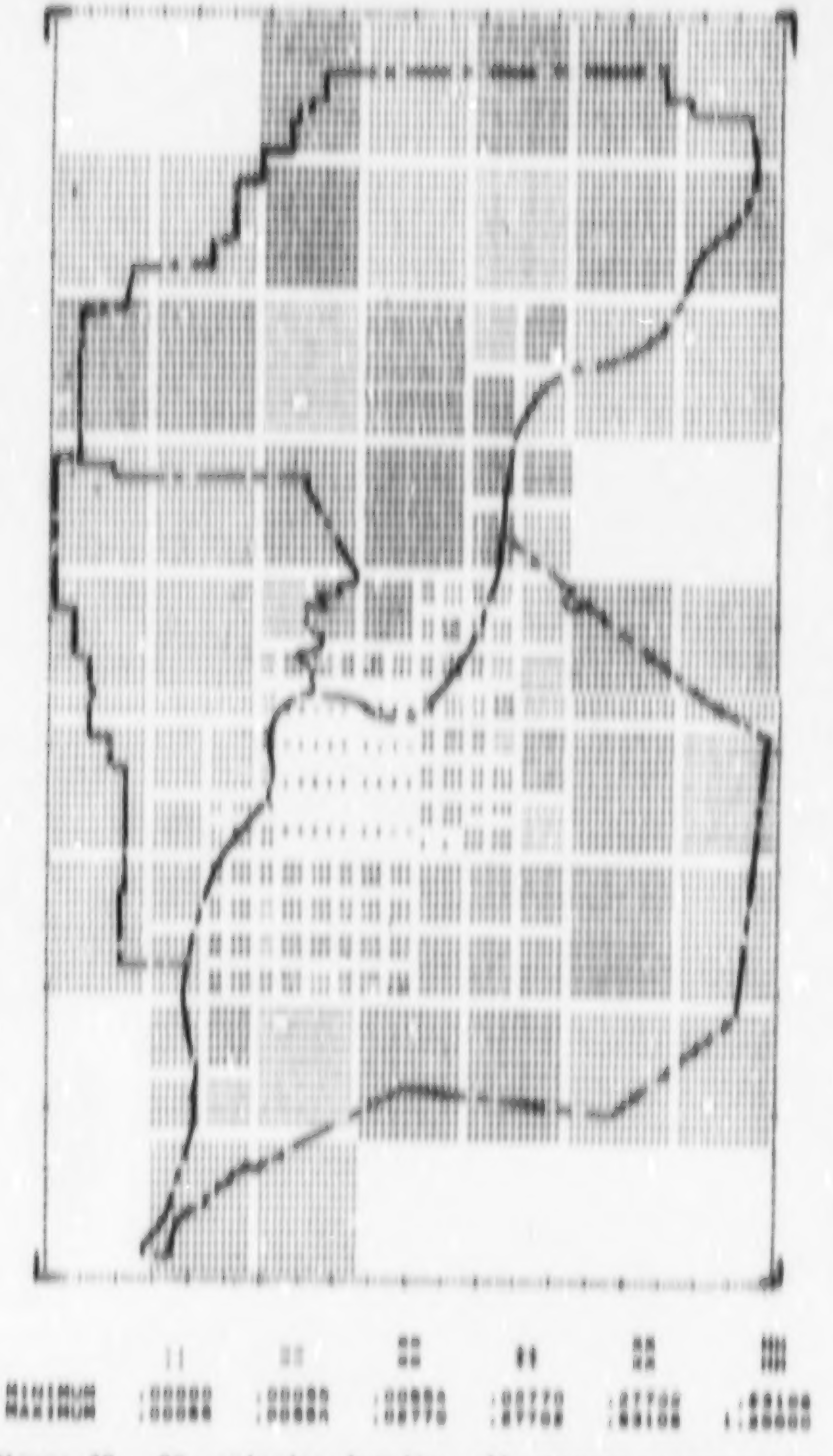

MINIMUM
MAXIMUM
.00000
.00088
.00088
.00854
.00854
.08770
.08770
.27702
.27702
.88108
.88108
1.20000

Figure 30. SO$_x$ emission density, all sources at upper limit
(tons per day per square kilometer)

upper limit the first receptor, R083, has an upper bound in the problem of 61.98 micrograms per cubic meter. (The concentration at this receptor due to non-EDZ sources is thus 80 - 61.98, or 18.02.) The upper bound on this receptor could be changed to any value between 61.97 and 62.03. The total emissions; i.e., the objective function, would decrease or increase, respectively, at a rate of 0.66 tons per day per unit change in the receptor's upper bound. At the values 61.97 or 62.03, emission source 9404021 (a light industrial point source) currently in the basis would have its emission density limit set at, respectively its lower or upper bound. For changes in the receptor's upper limit beyond 61.97 or 62.03, the rate of change of the objective function would be different and other emission sources besides 9434021 would be affected. Similar information is given for the other receptor at its upper limit.

The second part provides similar information for each column at the limit level. For example, the first source given is 200012 (a commercial area source, future development) is at its upper bound, 0.18790 tons per square kilometer per day, in the optimal solution. It has a planned area of 1.94 square kilometers. The sensitivity analysis indicates that if its area were reduced to 1.15 square kilometers its emission density limit would be set at 0.42 tons per square kilometer. Total regional emissions would decline 0.80 tons per day per unit decrease in this source's emission density limit. Any change in this source will affect the emission density limit of source 9404021, currently in the basis. If source 200012's emission density limit were set below 0.42 tons per square kilometer, source 9404021's emission density limit would be set at its upper bound. Similar information is presented for all of the emission sources.

The third part indicates the sensitivity of the solution to changes in the ambient concentrations at receptors not at their upper limit. The first receptor is at 33.47 micrograms per cubic meter in the optimal solution. Its upper bound is 71.6 micrograms per cubic meter. However, the upper bound can be changed down to 33.40 before an emission source whose emission density limit currently at its upper bound will be forced to change.

The last part provides information on sources not at their upper or lower bound. For example, source 9494921 is currently in the basis with an emission density limit of 18.1 tons per square kilometer. Its upper and lower bounds are 19.4 and 15.5, respectively. It can however, change only between 18.2 and 18.0 before another source, currently at its upper or lower bound, will be affected.

The examples given above are typical of the sensitivity of the solution to the right hand side and bounds of all the receptors and sources. As was the case in Baltimore, it is highly sensitive.

Solution - 100 Percent Sample

The emissions maximization was also executed for the full complement of receptors to determine the sensitivity of the optimal solution to differing receptor sets. With the full receptor set, the linear program failed to reach an optimal solution. That is, with all sources set at their lower limit, the NAAQS is still exceeded. Two receptors, not included in the 40 percent execution, showed projected ambient concentrations of, respectively, 10 and 6 μg/m^3 in excess of the standard. Several receptors in the vicinity of these receptors; i.e., 1 kilometer distant, that were included in the 40 percent execution showed projected concentrations of 15 to 20 μg/m^3 less than the standard. Inspection of the emission inventory indicated several point sources with low stack heights in the immediate vicinity of these two receptors.

Unlike the infeasible particulate matter example, in which nearly half of the receptors over a broad area exceeded the NAAQS, the infeasible 100 percent sulfur oxide example is due to a hot spot with most receptors well below the NAAQS. The appropriate action would be to prepare a summary of each source's contribution to the two receptors and review the upper and lower bounds on the emission density for each significant source. Some form of source specific emission limits may well be appropriate. In conclusion, several observations can be made.

- The same pattern of emission density limits set in Baltimore by the emissions maximization formulation were set by this model in Louisville; i.e., more stringent emission density limits in the center of the region and less stringent ones on the periphery.

- It is possible that even though the NAAQS is currently being attained, the standard may be violated due to planned growth even if all growth is at the specified lower emission density limit. In such cases, the linear program will reach an infeasible solution. The emission density of any one or all three classes of sources must then be reduced; viz., non-EDZ sources, existing EDZ sources, and planned future development.

- The model can be sensitive to the number and location of receptors. In the extreme, an infeasible solution may be reached with a full complement of receptors when a feasible solution is reached with a subset of receptors. If the receptor locations are valid, an analysis of source contributions to the receptors exceeding the standard should be used to further define the problem.

- To conserve resources, it may be appropriate to run the model with a subset of receptors. When a satisfactory optimal solution has been achieved, the model must then be rerun with all receptors. The preliminary optimal solution can serve as a starting point for the rerun with all receptors.

SECTION IX

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APPENDIX A

AN INTRODUCTION TO LINEAR PROGRAMMING

Linear programming is a mathematical technique whereby a linear function of several variables is maximized (or minimized) when the variables are subject to various constraints. The linear function that is maximized is referred to as the objective function; it is usually some kind of economic or policy objective such as profit, output, or, in the problem at hand, the maximization of the emissions of air pollutants or the minimization of costs imposed on sources of emissions. For example, the objective function of a linear program that maximizes emissions would be:

$$\text{maximize emissions, } E = a_1 E_1 + a_2 E_2 \ldots\ldots + a_n E_n \qquad (17)$$

where E_1, E_2 .... and E_n are the variables (the emission density limits in tons per day per acre) and a_1, a_2, and a_n are the constants (the lot area of each emission source). All the E's are of the first power, which is necessary to characterize the relationship as a linear equation.

Each of the variables, E_1, E_2 .... and E_n, are subject to some constraint. In the problem at hand, the air quality at a specified receptor must not exceed a specified level. Specifically:

$$t_1 a_1 E_1 + t_2 a_2 E_2 \ldots\ldots + t_n a_n E_n \leq S \qquad (18)$$

where t_1, t_2, ... t_n are the transfer coefficients relating unit emissions at each source to the ambient concentration at the receptor. The sum, over all sources, of t_n a_n E_n must be less than or equal to the standard.

It is useful to consider the graphic solution to a simple problem with two emission sources and two receptors. Assume the maximum ambient concentrations desired at receptor 1 is 12 μg/m³ and at the second receptor, 8 mg/m³. The areas and transfer coefficients are as follows:

	Area, acres	Transfer coefficient, $\frac{\mu g/m^3}{\text{tons/year}}$	
		To receptor no. 1	To receptor no. 2
Source 1	6	0.33	0.33
Source 2	7	0.43	0.14

The maximization problem would then be formulated as:

$$\begin{aligned} \text{Maximize:} \quad & 6\ E_1 + 7\ E_2 \\ \text{Subject to:} \quad & 2\ E_1 + 3\ E_2 \leq 12 \\ & 2\ E_1 + E_2 \leq 8 \\ & E_1,\ E_2 \geq 0 \end{aligned} \tag{19}$$

In Figure 1 the two constraining equations are shown. All points to the left of the inequality:

$$2\ E_1 + 3\ E_2 \leq 12 \tag{20}$$

are possible (feasible) combinations of E_1 and E_2. Similarly, points to the left of the second constraint inequality are feasible.

The hatched region in Figure 31 is the set of points that are feasible under all constraints; it is the feasible region. Clearly, not all of these points will maximize emissions.

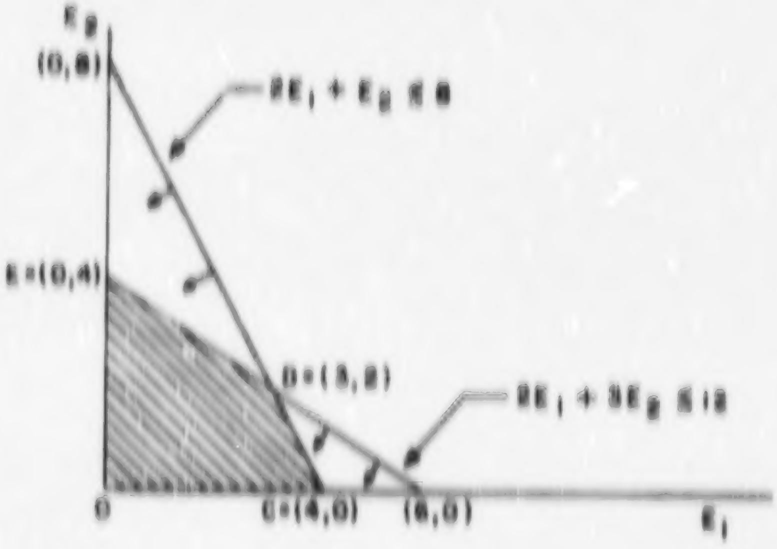
E_2
(0,8)
$2E_1 + E_2 \le 8$
E=(0,4)
D=(3,2)
$2E_1 + 3E_2 \le 12$
0
C=(4,0)
(6,0)
E_1

Figure 31. Construction of feasible region

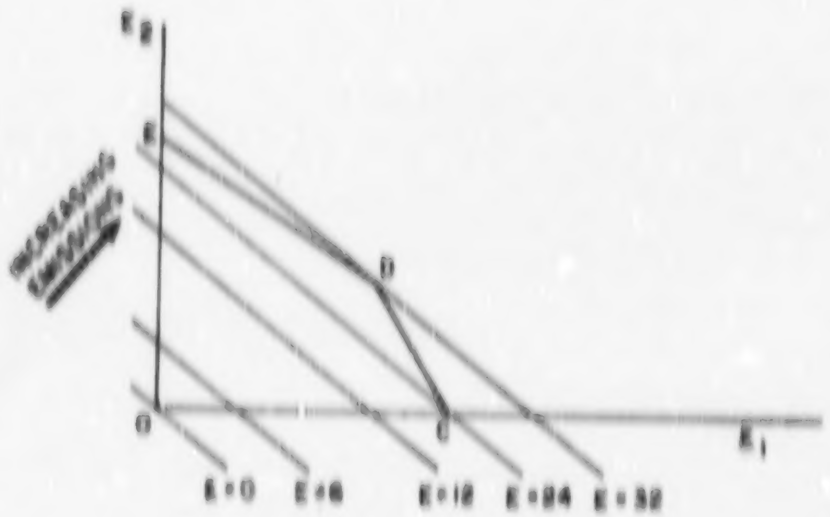
E_2
E
INCREASING EMPLOYMENT
D
0
C
E_1
E=0
E=6
E=12
E=24
E=32

Figure 32. Determination of optimal solution

The family of objective functions is shown in Figure 32. Each line is the set of points with constant amounts of aggregate emissions. Consider the objective function for which total emissions, E, equals 16. This line contains many feasible points, all of which give us 16 tons per year of emissions. But the line E = 24 is better, because it contains points with 24 tons per year. Best of all is the line E = 32. Here there is only one point in the feasible region, D, and this is the optimal solution. The optimal solution is to set an emission density limit of 3 tons per year per acre for emission source No. 1 and 2 tons per year per acre for emission source No. 2. At any other combination of emission limits, either the desired ambient air quality levels of 12 and 8 micrograms per cubic meter would be violated or the sum of emissions over the two sources would be less than 32 tons per year.

For a more detailed and comprehensive treatment of the subject, the reader is referred to any standard text on the subject, such as:

- W. Baumol, Economic Theory and Operations Analysis[23]
  S. Vajda, Readings in Linear Programming[24]
  F. Hiller, G. Lieberman, Operations Research[25]

These references also note more advanced texts.

APPENDIX B

PROVISION FOR SHORT-TERM STANDARDS IN AIR QUALITY CONSTRAINT

The air quality constraint in the emission density limit setting model, equation (8), viz.,[*]

$$\sum_j \sum_k t_{i,j,k,\ell} \sum_m (E_{j,k,\ell,m}\, a_{j,k,m}) \leq S_{i,\ell} - b_{i,\ell} - f_{i,\ell} - p_{i,\ell} - r_{i,\ell} - n_{i,\ell} \quad \Big| \text{ for all } i,\ell \qquad (21)$$

states that the sum, over all sources, of the product of the emissions from each source and a transfer coefficient between that source and a specified receptor i shall not exceed the air quality standard at that receptor. The transfer coefficients, derived through the execution of AQDM, relate the effect of annual emissions at a specific source to the ambient concentration at a specified receptor i. Thus, through the use of this relatively straightforward constraint, it is possible to set a pattern of emission density limits such that the annual ambient air quality standards, expressed as arithmetic means, are not violated.

One problem with this formulation, however, is that the annual standard for particulate matter, 75 μg/m³, is an annual geometric mean. For the receptors in the EDZ model that are monitoring stations, it is possible to convert the geometric mean to an expected arithmetic mean that is equivalent to the annual particulate matter standard, if one assumes a log-normal distribution, via,

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[*] The variable definitions of Section V are employed.

$$m = m_g \exp (0.5 \ln^2 s_g) \qquad (22)^a$$

where m = arithmetic mean
m_g = geometric mean
s_g = geometric standard deviation

For example, the geometric standard deviation at the St. John's College monitoring station in the Baltimore AQCR is 1.5 (see Table 8). Substituting in Equation (22), one obtains

$$m = 81.4 = 75 \exp (0.5 \ln^2 1.5) \qquad (23)$$

Ignoring the effects of calibration, one would substitute 81.4 in place of $x_{i,\ell}$ for the i corresponding to the St. John's College receptor and the ℓ corresponding to particulate matter.

The question remains, however, of how to treat the majority of the receptors in the EDZ model that are not monitoring stations and therefore have an unknown geometric standard deviation. If a geographic pattern existed among the observed geometric standard deviations, it would be

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[a] For the convenience of the reader familiar with A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards,[14] EPA Publication AP-89, the indicated equations in this appendix correspond to rearrangements or combinations of the following equations in AP-89.

Equation number	AP-89
22	11
24	21
25	26
26	21,11

Table 8. 1974 TSP CONCENTRATIONS RECORDED AT MONITORING STATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
St. John's College Anne Arundel Co.	53	135	126	51	47	1.5
Overlook School Anne Arundel Co.	53	184	136	66	62	1.5
Arundel High School Anne Arundel Co.	56	169	115	52	47	1.6
Glen Burnie Public Works Anne Arundel Co.	62	196	162	80	65	2.7
Route 176 & 170 Anne Arundel Co.	53	182	153	65	58	1.6
Harwood High School Anne Arundel Co.	48	137	119	47	43	1.5
Fire Dept. HQ Baltimore	107	282	253	117	102	2.0
Sun Ave. Fire Dept. Baltimore	79	326	317	146	136	1.6
NE Police Station Baltimore	100	175	143	60	53	1.6

Table 8 (continued). 1976 TSP CONCENTRATIONS RECORDED AT MONITORING STATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
NW Police Station Baltimore	91	190	171	74	68	1.5
NE Police Station Baltimore	73	309	287	120	105	1.7
SW Police Station Baltimore	160	309	236	96	86	1.6
3001 Eastern Blvd. Baltimore Co.	53	172	113	57	49	2.1
Fort McHenry Baltimore	56	329	221	116	103	1.6
1270 Linwood Ave. Baltimore	58	265	263	108	95	1.7
Sewage Disposal Plant Baltimore	52	291	266	126	113	1.6
Ft. Howard VA Hospital Baltimore Co.	116	187	156	55	50	1.6
Garrison Police Barracks Baltimore Co.	47	123	122	55	49	1.7

Table 8 (continued). 1974 TSP CONCENTRATIONS RECORDED AT MONITORING STATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
Catonsville Library Baltimore Co.	47	141	91	51	46	1.6
County Office Bldg. Harford Co.	53	130	122	56	51	1.5
Dundalk Baltimore Co.	108	203	176	86	76	1.6
Essex Baltimore Co.	53	158	155	69	62	1.5
Whiteford Harford Co.	58	96	86	39	35	1.6
Simpsonville Howard Co.	61	145	116	51	46	1.6
Goucher College Baltimore Co.	76	135	110	54	48	1.7
Carroll Co. Hospital Carroll Co.	52	207	132	58	43	1.7

Source: SAROAD data system.

possible to use that pattern to assign deviations to the receptor grid in BDE. A plot of the location of the monitoring stations and geometric standard deviations is shown in Figure 33. In our view a convincing pattern does not exist. If a pattern does not exist, an alternative is to use the mean of the recorded data, in this case 1.67. Substituting in equation (22), one calculates a value for the expected arithmetic mean of 85.54 $\mu g/m^3$. Therefore, this value would be used as the standard at every receptor in the grid.

In this example, the observed geometric standard deviation, obtained from SAROAD* printouts, was utilized. In the actual execution of the decision model it is more appropriate to compute the geometric standard deviation using the following formulas.

$$s_g = (c_{max}/m_g)^{1/z} \qquad (24)$$

where c_{max} is the maximum 24-hour observations, and

z is the z deviate of the normal distribution corresponding to a frequency calculated by

$$f = 1 - \frac{1 - 0.4}{n} \qquad (25)$$

where n = the number of valid 24-hour observations.

The use of formulas 24 and 25 allows the calculation of a geometric standard deviation from the top half of a distribution, which most closely fits the frequencies associated with the standard.

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*Storage and Retrieval of Aerometric Data.

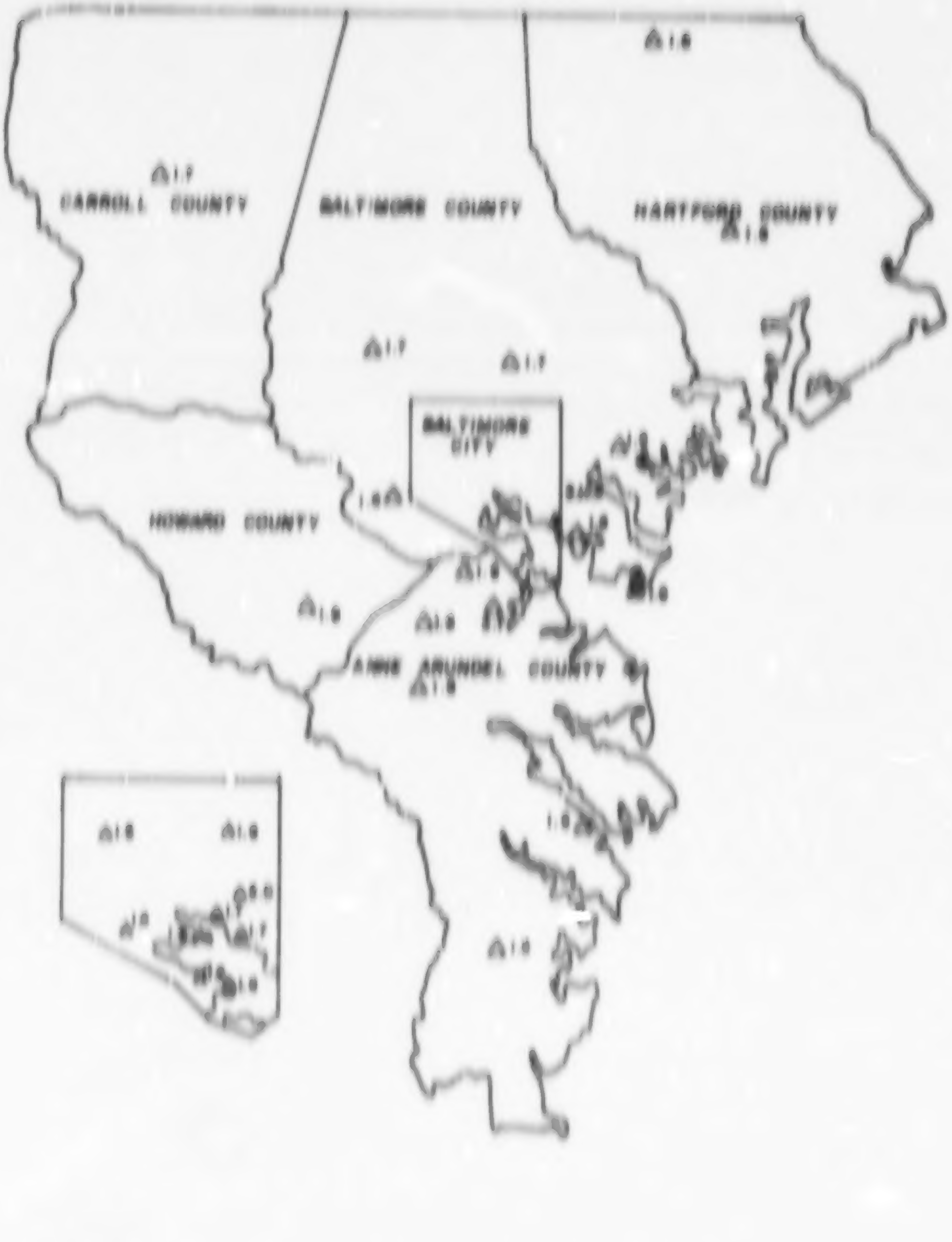
CARROLL COUNTY
BALTIMORE COUNTY
HARTFORD COUNTY
BALTIMORE CITY
HOWARD COUNTY
ANNE ARUNDEL COUNTY

Figure 33. Location of TSP monitoring stations and associated geometric standard deviation

The assumption of a log-normal distribution also allows the consideration of the 24-hour standards in the emission density limit setting model. The ability to make this assumption is critical, in that there is no other way to consider the short-term standard and maintain a relatively simple EDL model which would be easily implemented.

The treatment of the short-term standards would proceed in a manner analogous to the estimation of an arithmetic mean equivalent to the geometric mean particulate standard. For example, in the case of sulfur dioxide, the average geometric standard deviation measured in the Baltimore AQMA is 2.76 (see Table 9). Assuming log normality, the second highest 24-hour concentration would be related to the arithmetic mean as follows.

$$x_{\text{2nd max}} = m\, s_g^{\,z - 0.5 \ln s_g} \tag{26}$$

The appropriate z deviate would be 2.62.[8] The 24-hour sulfur dioxide standard is 365 ug/m^3. Accordingly, rearranging Equation (26) to solve for m,

$$m = 365\, s_g^{\,0.5 \ln s_g - 2.62} \tag{27}$$

Substituting 2.76 for s_g, one obtains an arithmetic mean of 42.7 ug/m^3. Since this is more stringent than the annual standard of 80 ug/m^3, it would be used in Equation (21) for $x_{i,k}$ where k corresponds to sulfur oxides.

---

[8] The use of the second highest 24-hour concentration in a year as the "design value" means that the standards will be violated (second highest concentration exceeding standard) on the average of every other year. As an alternative, it has been suggested[15] that the annual maximum concentration be used as the design value. If this is done, the ambient short-term standards would probably be violated in 1 year out of 8. A Z deviate of 3.04 would be used instead of the 2.62 used above.

Table 9. 1974 SO_x CONCENTRATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
St. John's College Anne Arundel Co.	51	152	74	20	9	3.4
Arundel High School Anne Arundel Co.	50	150	92	23	13	3.2
Glen Burnie Public Works Anne Arundel Co.	53	162	128	30	17	3.1
Routes 176 & 170 Anne Arundel Co.	55	121	86	18	11	2.9
Harwood High School Anne Arundel Co.	49	61	58	13	8	2.9
Calvert & 22nd Sts. Baltimore	51	120	109	26	13	3.6
2001 Eastern Blvd. Baltimore	43	65	33	8	5	2.3

Table 9 (continued). 1974 SO_x CONCENTRATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
Fort McHenry Baltimore	56	169	166	77	66	2.0
1050 Linwood Ave. Baltimore	55	106	102	24	13	3.1
Sewage Disposal Plant Baltimore	52	286	262	70	58	2.6
Ft. Howard VA Hospital Baltimore Co.	108	76	68	18	11	2.7
Garrison Police Barracks Baltimore Co.	44	41	31	9	6	2.5
Catonsville Library Baltimore Co.	45	40	26	8	5	2.3
County Office Bldg. Harford Co.	61	80	65	19	12	2.6

Table 9 (continued). 1974 SO$_x$ CONCENTRATIONS IN THE BALTIMORE AQMA

Monitoring stations	Number of observations	Maximum 24-hr	Second highest	Arithmetic mean	Geometric mean	Geometric standard deviation
Dundalk Baltimore Co.	108	189	156	33	16	3.7
Essex Baltimore Co.	56	110	98	29	20	2.6
Whiteford Harford Co.	58	35	28	7	5	2.3
Simpsonville Howard Co.	59	56	39	12	9	2.3
Goucher College Baltimore Co.	73	117	90	18	11	2.7
Carroll Co. Hospital Carroll Co.	48	56	48	14	9	2.6

Source: SAROAD data system.

In a similar fashion, the annual arithmetic mean equivalent to the 24-hour particulate standard can be computed. Using Equation (27), one obtains

$$m = 150\, s_g^{0.5 \ln s_g - 2.62} \qquad (28)$$

Substituting 1.67 (the average in Baltimore) for s_g, one calculates a value of 44.6 for the expected arithmetic mean equivalent to a 24-hour standard of 150 ug/m^3. As this also is more stringent than the expected arithmetic mean, 85.5, equivalent to the annual standard, the value of 44.6 ug/m^3 would be used in equation (21) for $x_{i,k}$ where k corresponds to particulates.

APPENDIX C

THE SO_x-PM FEASIBILITY CONSTRAINT

The sulfur oxides emission density-particulate matter emission density feasibility constraint is based on the premise that sulfur oxide emission densities and particulate matter emission densities are not independent. The utilization of this constraint in the decision model will avoid the assignment of a certain emission density to a component area for one pollutant and the subsequent assignment of an emission density for the other pollutant that is so stringent that the emission density for the former pollutant could never be utilized.

Assuming that the respective emission rates are not independent, moreover, that they are linearly related, one could expect to obtain a scattergram such as that shown in Figure 34. The regression line estimating this relationship, $PM = \hat{a} + \hat{b}\, SO_x$, is shown as a solid line. The intercept, $\hat{a}$, and the slope, $\hat{b}$, are estimated values; one can compute a confidence interval for the regression line. In particular,

$$Y_0 = \hat{a} + \hat{b} X_0 \pm t_{\epsilon/2}\, \hat{\sigma}_\mu \sqrt{1 + \frac{1}{n} + \frac{(X_0 - \bar{X})^2}{\Sigma x^2}} \qquad (29)^*$$

For a given sulfur oxide emission rate, X_0, one would then constrain the particulate matter emission rate, Y_0, to be greater than or equal to

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[*] See, for example, J. Johnston, Econometric Methods, McGraw-Hill, 1972.

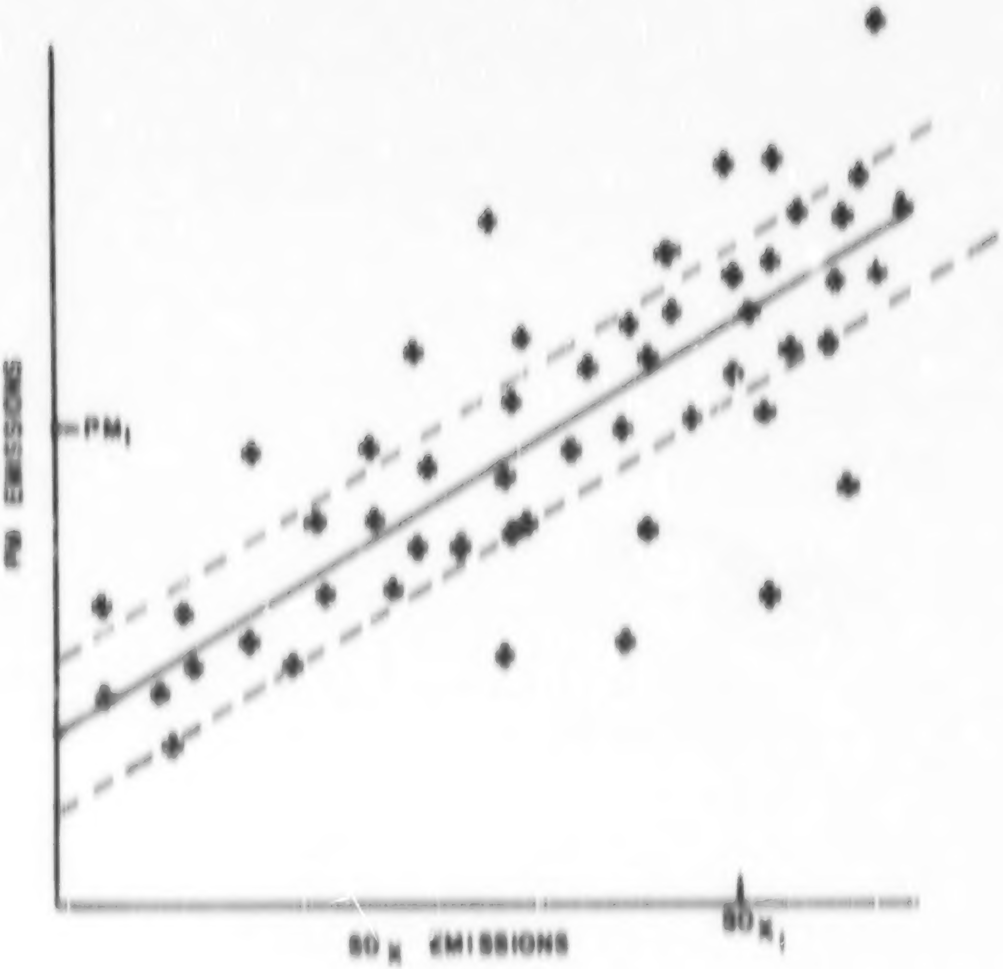

Figure 34. Hypothetical relationship between SO$_x$ and PM emissions

the lower boundary. However, since X_0 appears underneath the radical, this cannot be easily employed in a linear program. It is an expedient approximation, though of no statistical meaning, to use the confidence interval for the mean of Y given the mean of X. Specifically,

$$\pm\ t_{\alpha/2}\ \hat{\sigma}_\mu \sqrt{\frac{1}{n}} \qquad (30)^*$$

The dotted lines in Figure 34 show what the extremes of this interval may look like. The constraint equation would then be

$$a_{j,k,m}\ X_{j,k,t=1,m} \geq \hat{a} - t_{\alpha/2}\ \hat{\sigma}_\mu \sqrt{\frac{1}{n}} + \left(\hat{b}\ a_{j,k,m}\ X_{j,k,t=2,m}\right) \qquad (30)$$

which reduces to

$$X_{j,k,t=1,m} - \left(\hat{b}\right) X_{j,k,t=2,m} \geq \left[\frac{\hat{a} - t_{\alpha/2}\ \hat{\sigma}_\mu \sqrt{\frac{1}{n}}}{a_{j,k,m}}\right] \qquad (31)$$

denoting the slope term in parentheses as ${\mu_k}^b$, and the term in brackets as ${\mu_k}^a$, this can be expressed as

$$X_{j,k,t=1,m} - {\mu_k}^b\ X_{j,k,t=2,m} \geq {\mu_k}^a \qquad (33)$$

which is the first SO_x-H feasibility constraint in the emissions maximization decision model described in Section V.

In the execution of the model, one would specify the confidence level of the interval by selecting a specific t, say 80 percent.

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*See Johnson, op. cit.

As was stated previously, the necessity of this constraint depends on the existence of a relationship between sulfur oxide and particulate matter emissions, after the application of existing regulations. If such a relationship does not exist, then this constraint is superfluous. The setting, in a specific component area, of a relatively high sulfur oxide emission density and low particulate matter emission density, or the converse, would only encourage those sources that have such emission characteristics to locate in that component area.

The existence of such a relationship would have to be tested for each time EDZ is implemented in an AQMA. Whether it existed would depend on the characteristics of the emission sources in an AQMA of a particular land use category and the homogeneity of these sources. One should note that this independence may exist only for some of the land use categories.

An inspection of the point source emission inventory in Baltimore and Louisville would suggest that, in these AQMAs, emission rates for the two pollutants are independent in the case of the heavy industrial land use category. Sulfur oxide and particulate matter emission rates for this category are plotted in Figure 35. Each asterisk represents one point source and a number represents the position of multiple sources. The lack of a linear relationship between sulfur oxide and particulate matter emission rates is adequately documented by the correlation coefficient. Figure 36 shows the relationship between emission rates for all heavy industrial point sources emitting less than 100 tons per year. No linear relationship is evident. (In fact, it could be more accurately described as a hyperbolic or reciprocal relationship, rather than linear.) Light industrial point source emission rates are plotted in Figure 37. Again, there is little linearity evident. Figure 38 shows the relationship between emission rates for noncoal burning commercial point sources. The R^2 is 0.7, which would suggest a relationship exists. The regression line has been drawn in as a solid line; however, it appears to have been greatly influenced by a half dozen relatively large sources. A more appropriate regression line is shown as a dashed line.

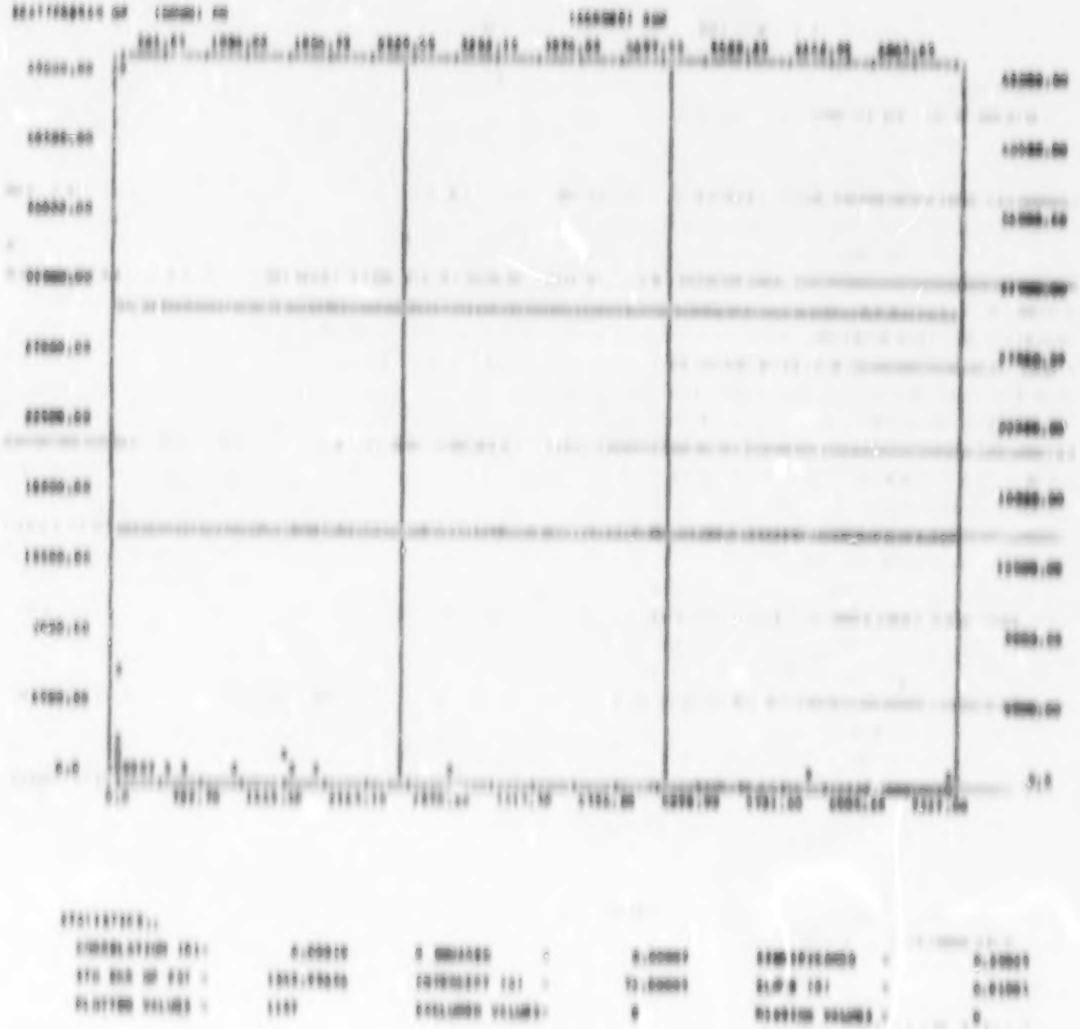


Figure 35. Plot of Baltimore heavy industrial point source PM emission rates versus SO_x emission rates (tons/year) (note: '9' indicates 9 or more observations)

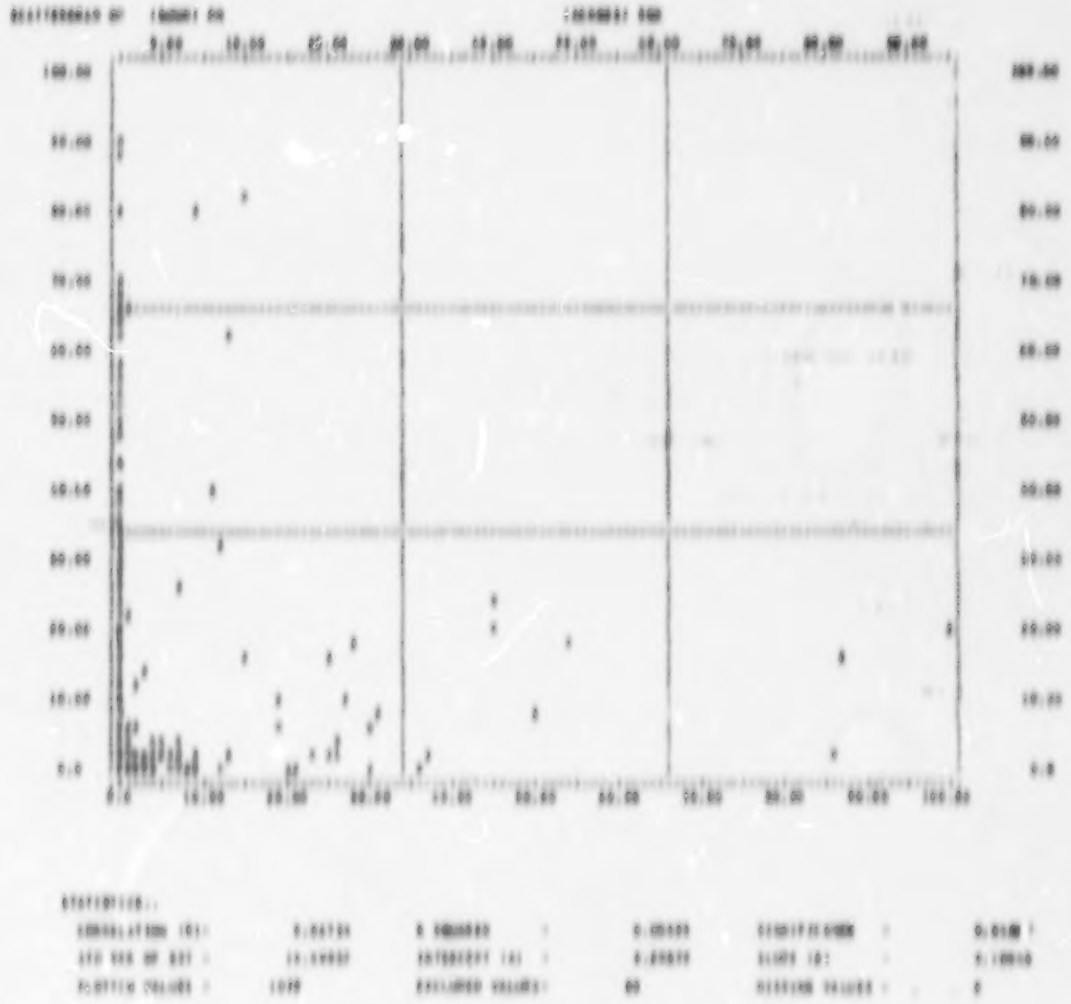
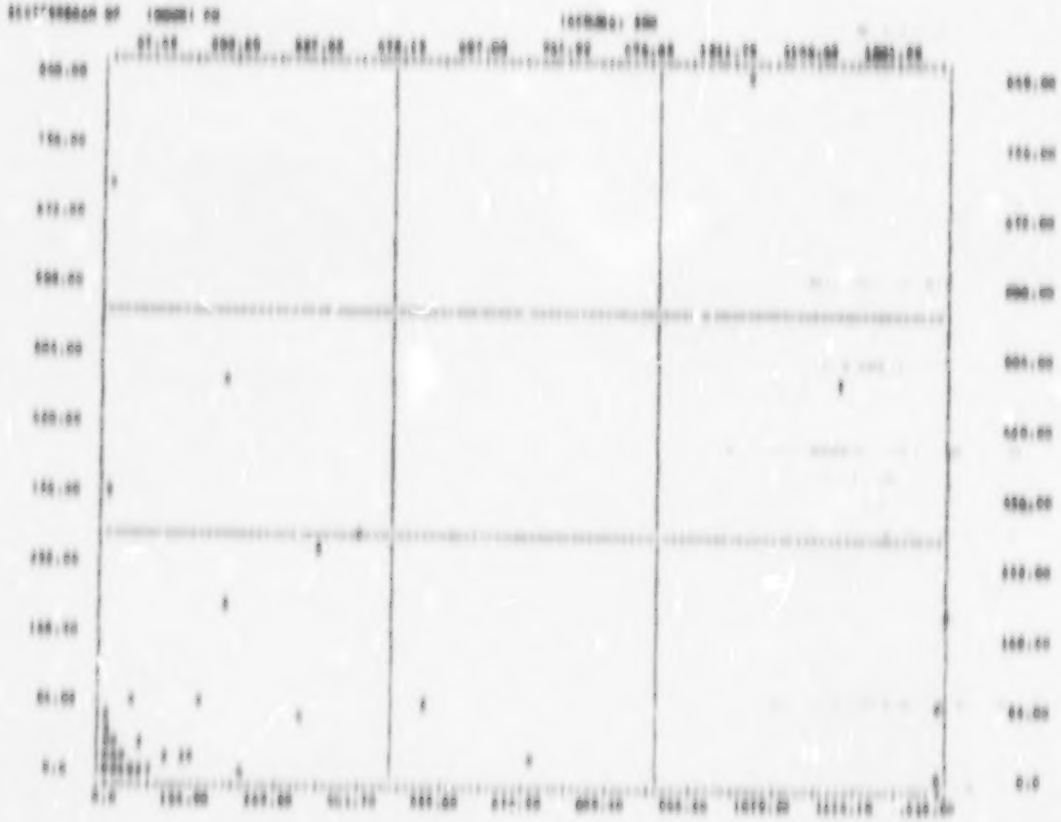


Figure 36. Plot of Baltimore heavy industrial point source PM rates versus SO_x emissions rates, sources with emissions less than 100 tons/year (note: '9' indicates 9 or more observations)



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STATISTICS..
 CORRELATION (R)-     [illegible]   R SQUARED        -   [illegible]   SIGNIFICANCE    -   [illegible]
 STD ERR OF EST -     [illegible]   INTERCEPT (A)    -   [illegible]   SLOPE (B)       -   [illegible]
 PLOTTED VALUES -     [illegible]   EXCLUDED VALUES-     0             MISSING VALUES -    0
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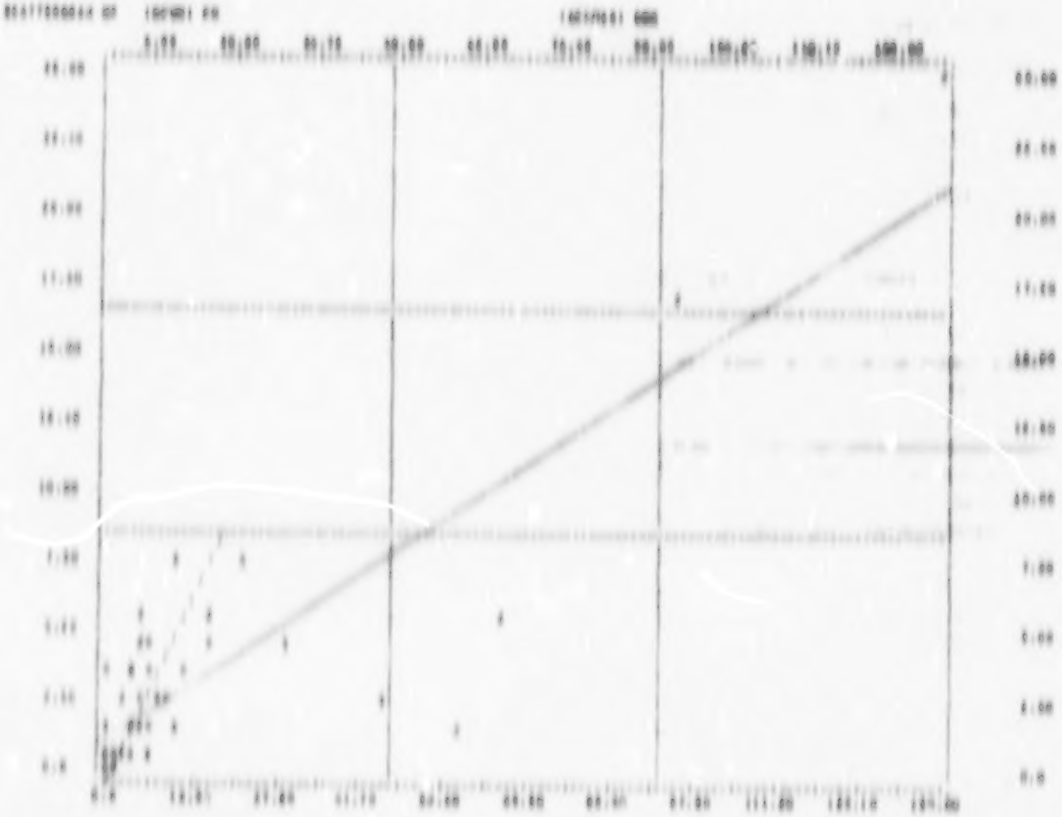
Figure 37. Plot of Baltimore light industrial point source PM emission rates versus SO_x controlled emission rates (tons/year) (note: '9' indicates 9 or more observations)



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STATISTICS..
 CORRELATION (R)-     [illegible]    R SQUARED       -    [illegible]    SIGNIFICANCE   -    [illegible]
 STD ERR OF EST -     [illegible]    INTERCEPT (A)   -    [illegible]    SLOPE (B)      -    [illegible]
 PLOTTED VALUES -   106              EXCLUDED VALUES-   0                MISSING VALUES -   0
```

Figure 38. Plot of Baltimore commercial point source PM emission rates versus SO_x controlled emissions rates, excluding coal burning sources (tons/year) (note: '9' indicates 9 or more observations)

In summary, a relationship between emission rates should be tested for on a sample from the base year emission inventory, stratified according to the land use categories contemplated for emission density regulation. If one exists, it is prudent to include a feasibility constraint, as discussed above, in the decision model.

APPENDIX D

SPECIFICATION AND UTILIZATION OF CONTROL COST PARAMETERS

Both formulations of the control cost minimization objective function (i.e., model nos. 1 and 3 of Section V) require an estimate of incremental control cost functions for future emission sources. The ability to estimate these functions is limited by two problems — the need to forecast adequately the nature of future emission sources and the need to estimate control cost functions that can be used in the linear programs. The discussion below is limited to industrial sources, as the control cost linear programs would likely be applied only to that source category.

At best, one can identify those areas that are planned for heavy and light industry. Within each of those categories, regional employment projections would give some indication of the most likely SIC[a] code categories, probably, at best, on the two-digit level. One could either use the industry with the largest employment growth or, within the top 5 or 10 categories, the heaviest polluting industrial category as a prototype heavy (or light) industry. Using this prototype, one would endeavor to estimate the incremental control costs.

For example, in Baltimore the U.S. Water Resource Council projections,[11] shown below in Table 10, indicate that primary metals (SIC code 33) and chemicals (SIC code 28) are the two industrial categories that will experience the largest absolute growth. One could use the control costs associated with the primary metals industry as the "c" parameters for future heavy industrial sources. On the other hand, most of the growth in SIC code 33 may represent the utilization of existing capacity and the capacity expansion of existing sources. In such a situation, it would be appropriate to use another industrial class.

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[a] Standard Industrial Classification.

Table 10. 1980 TO 1990 PROJECTIONS OF GROWTH IN MANUFACTURING EARNINGS ($000)

Heavy Industry		Light Industry	
26	28,000	20	12,300
27	55,400	22	11,000
28	65,500	23	12,700
29	1,400	24, 25	12,500
30		34, 19	65,300
31		35	69,700
32		36	26,800
33	85,100	371	28,000
		37 ex 371	10,700
		21, 30-32, 38, 39	58,700

Source: Reference 33.

For the purposes of this example, we will assume that it is more appropriate to use SIC code 28, which is Chemicals and Allied Products. However, projections more detailed than two-digit SIC codes are needed to develop a control cost parameter. Unless more detailed employment projections are available, it would be consistent with AQMP emission projection methodologies to assume the characteristics of future sources to be similar to those of existing sources. Therefore, one would review the emission characteristics of existing heavy industrial point sources to develop the incremental cost of emission reductions. Given the specific characteristics of several prototypical sources, the control cost element of the Implementation Planning Program (IPP) package could be utilized to estimate the costs of an emissions reduction.

One would

1. Develop projections of regional industrial growth by at least two-digit SIC code. The OBERS projections or equivalent or superior projections available locally can be used.
2. For each two-digit SIC code, estimate the percentage of future growth occurring from:
   a. the utilization of existing industrial capacity
   b. capacity expansion of existing sources
   c. construction of new industrial facilities.

   This information can be derived from the regional economic projections and a survey of existing point sources conducted for the AQMP emission projection.
3. Rank order the existing point sources in each two-digit SIC code by their emission density after application of existing and projected regulations.
4. For both the heavy and light industrial categories, determine the probable two-digit SIC codes for new industrial facilities, based on the results of Step 2.
5. Identify prototypical point sources in the heavy and light industrial categories by selecting the existing point source with the highest emission density in the fastest growing two-digit SIC code. If, in either the heavy or light industrial category, growth in more than one two-digit SIC code is expected to contribute significantly to the construction of new industrial facilities, identify a prototypical point source for each one.
6. For each of the two or more prototypical point sources and for the expected capacity expansion at existing sources, execute the control cost segment of the IPP package and identify the annualized control costs for possible levels of emission reduction beyond existing and projected regulations.

The costs of specific levels of emission reduction cannot be directly used in equation (9). There is, however, a more complex formulation of a control cost minimization that employs integer programming, discussed in Section V, in which they can be used.

Before reviewing the specification and use of the cost parameter, it is convenient to develop a specific example. In the Baltimore AQMA, it was assumed that SIC code 28 was the fastest growing heavy industrial category. The first SIC code 28 point source in the Baltimore inventory is the Glidden Durkee paint plant, SIC code 2816. The particulate matter emission sources are summarized in Table 11. Table 11 also shows the various levels of emission reductions available by installing control equipment and the annualized cost of that equipment. The possibility of tandem devices is ignored. Based on this information, a schedule of control costs and emission reductions was prepared and is shown in Figure 39.

To use this information to specify the cost parameter, it is necessary to develop a linear approximation. A possible one is shown in Figure 40. Three line segments are shown with slopes of 13.86, 68.93, and 3528.08. Since the control cost – emission reduction schedule cannot be adequately approximated with a single line segment, one is faced with several cost parameters that could be used in the objective function.

The only feasible way to accomplish this, given the control cost minimization formulation in equation (9), is through successive solutions to the linear program.

For example, in the case of three future heavy industrial sources of the same area, one would first execute the following linear program.

$$\text{Max } E' = 13.86\, a_1 E_1 + 13.86\, a_2 E_2 + 13.86\, a_3 E_3 \qquad (34)$$

subject to:

air quality constraint: $\sum_j t_{i,j}\, a_j E_j \leq S_i \mid$ for all i

Table 11. EMISSION REDUCTIONS AND ASSOCIATED CONTROL COSTS

Source and control device	Device efficiency	Particulate emissions, tons/year	Capital cost, $	Annual operating cost, $	Total annualized cost, ignoring tax effects, $	Emission reduction	Average control cost per ton reduction, $
Calcination kilns (three)							
Uncontrolled	0	[illegible]	0	0	0	0	0
Low-efficiency cyclone	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Medium-efficiency cyclone	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Low-efficiency scrubber	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Medium-efficiency scrubber	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
High-efficiency scrubber	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
High-temperature fabric filter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rotary dryers (three)							
Uncontrolled	0	[illegible]	0	0	0	0	0
Low-efficiency scrubber	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Low-temperature fabric filter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ball mills (three)							
Uncontrolled	0	[illegible]	0	0	0	0	0
Low-temperature fabric filter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Boilers (five)							
Distillate oil		[illegible]	0	0	0	0	0
Natural gas		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]							
Uncontrolled		[illegible]					
Total uncontrolled emissions		[illegible]					

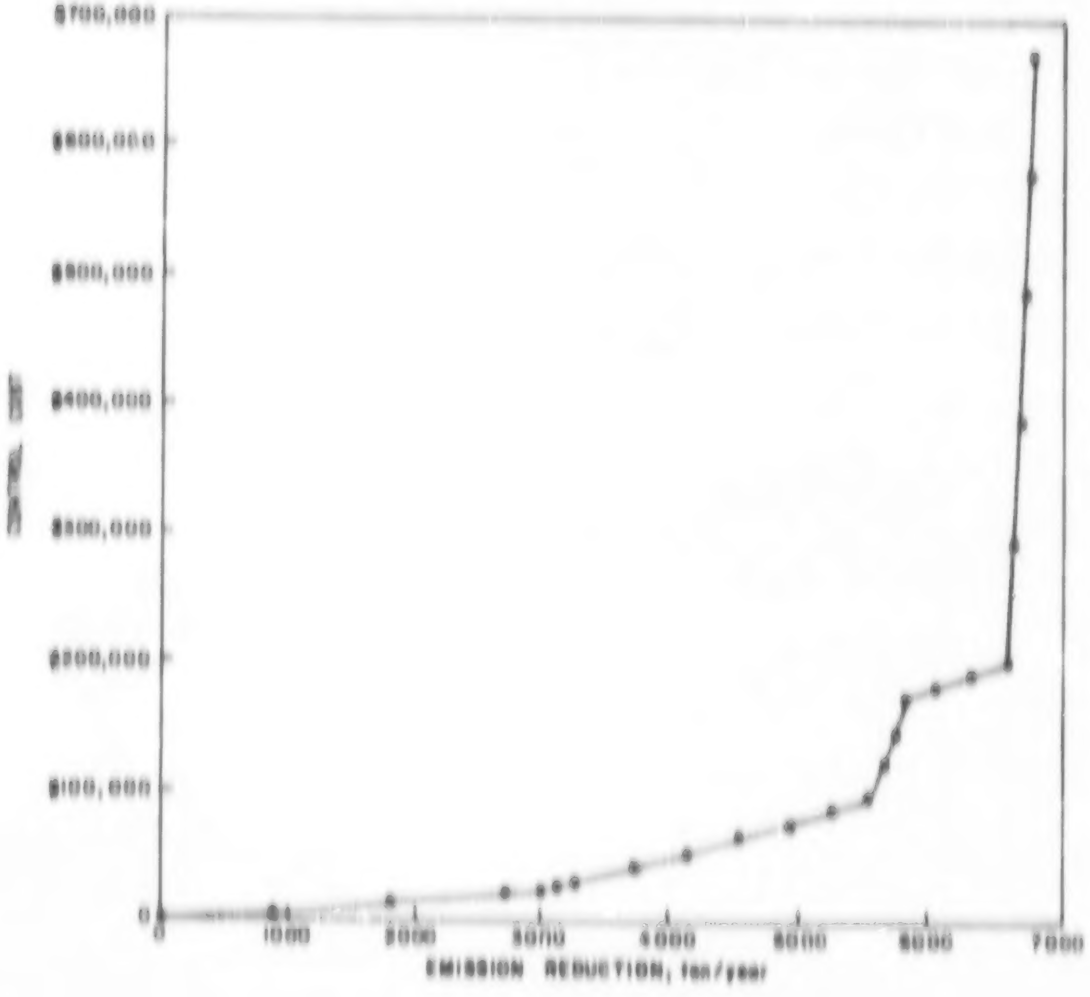

Figure 39. Schedule of emission reductions versus control costs for prototypical heavy industrial point source

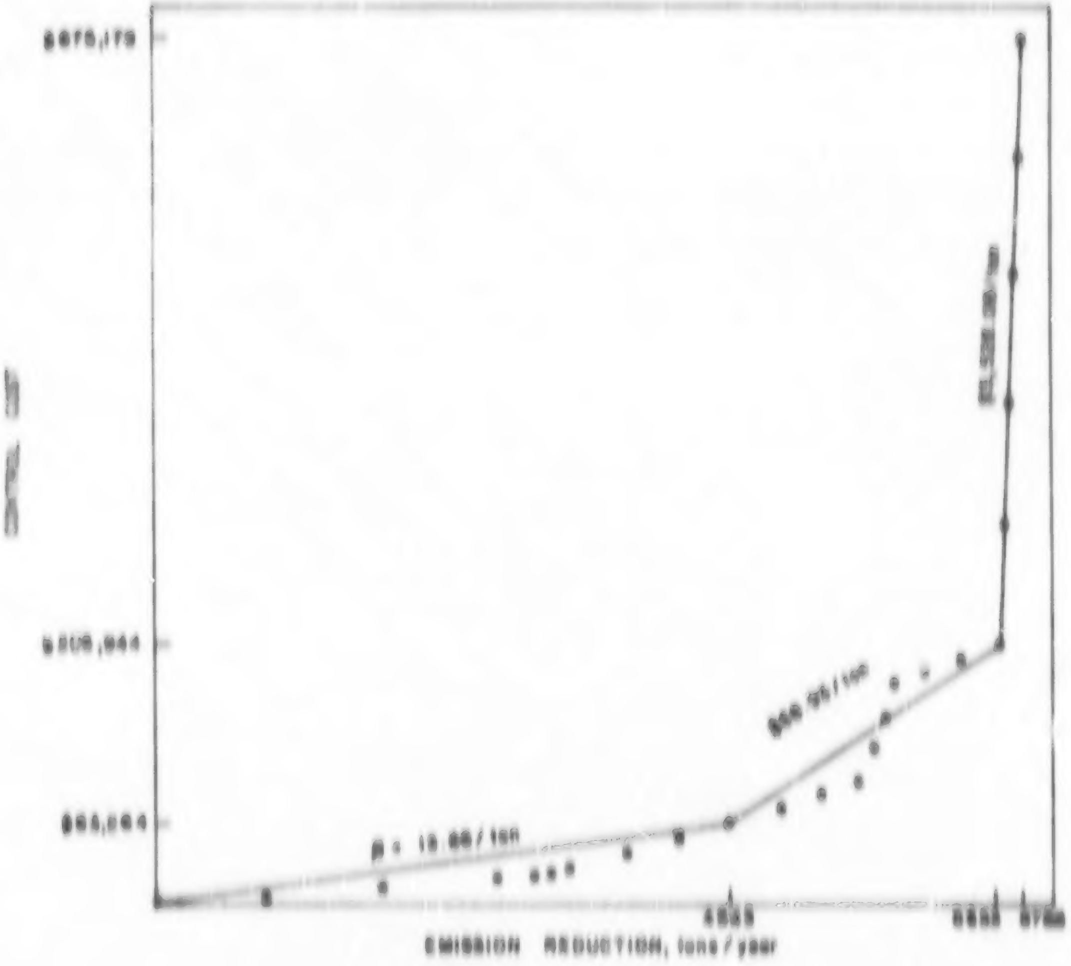

Figure 40. Plot of linear approximation of the control cost - emission reduction schedule

$$\left.\begin{array}{r} \text{technological constraint:}^{*}\ a_j\ E_j \ge 0 \\[1em] \text{zero cost constraint:}^{*}\ a_j\ E_j \le 4563 \end{array}\right|\ \text{for all } j$$

If, in any source j, the upper bound on E_j was binding, it may be possible to achieve a further emission reduction at that source. However, the incremental cost would no longer be 13.86; it would be 68.93. Therefore, one would rerun the program, substituting the parameters of the second line segment. In this instance, suppose the upper bound on the third E_j was binding; one would then rerun the linear program as follows.

$$\text{Max } Z' = 13.86\ a_1\ E_1 + 13.86\ a_2\ E_2 + 68.93\ a_3\ E_3 + 63266 \qquad (35)$$

subject to:

$$\text{air quality:}\quad \sum_j t_{i,j}\ a_j\ E_j \le S_i \ \Big|\ \text{for all } i$$

$$\begin{array}{r} \text{technological} \\ \text{constraints} \end{array} \left\{\begin{array}{l} a_1\ E_1 \ge 0 \\ a_2\ E_2 \ge 0 \\ a_3\ E_3 \ge 0 \end{array}\right.$$

$$\begin{array}{r} \text{zero cost} \\ \text{constraints} \end{array} \left\{\begin{array}{l} a_1\ E_1 \le 4563 \\ a_2\ E_2 \le 4563 \\ a_3\ E_3 \le 6633 - 4563 = 2070 \end{array}\right.$$

---

[*] The technological and zero cost constraints are specified for the nodes of a line segment on Figure 40, plot of linear approximation of the control cost-emission reduction schedule.

While one could use ordinary linear programming and rerun the model until all the upper and lower bounds were not binding or until the optimum solution did not change, it is expedient to use a special formulation of linear programming that will do this all at once; viz., separable convex programming.[18]

APPENDIX E

THE APPLICATION OF THE EMISSION DENSITY SETTING MODEL IN AN ATTAINMENT SITUATION

The models described in Section V and illustrated in Sections VII and VIII assume that all current emission sources, after the application of current or pending emission control regulations, will not be required to further reduce their emission rates under emission density zoning.[*] Emission density zoning is thus a technique for managing growth, both in terms of new emission sources and expansion of existing ones, as contemplated by air quality maintenance planning. Attainment of the NAAQSs is assumed.

In regions where the NAAQSs have not been attained or in those regions where the current ambient air quality levels are so close to the NAAQSs so as to preclude growth without reductions in emission levels of current sources, the models described in Section V are not applicable. The former situation will be apparent; the latter may not be so obvious. It is possible that the linear program will be unable to find a feasible solution; that is, if the region experiences the growth contemplated in the land-use plan, the NAAQSs will be violated, even if all new sources emit at minimum levels and current sources do not expand.[†] To achieve the NAAQSs it is necessary that current sources reduce their emission rates beyond that contemplated by existing emission control regulations.

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[*] Specifically, note the attainment constraint of Model No. 1 on page V-3.

[†] This is what happened in the Louisville particulate matter test case.

It is possible to implement emission density zoning in such a situation, though EDZ is more commonly thought of as a maintenance strategy than an attainment strategy. One has two options. The first is to impose additional emission control regulations on existing sources. If sufficient reductions are imposed it will then be possible for the linear program to find a feasible solution.

Alternatively, one can impose emission density limits that require existing sources to reduce their emission rates. To set such emission density limits in a model such as described in Section V, the lower bound on the emission density limit of existing sources should be set at a lower value. As formulated in model no. 1, the attainment constraint, viz.,

$$E_{j,k,t,m} \geq e^{base}_{j,k,t,m} \mid \text{for all } j,k,t; \text{ for } m = 1 \qquad (36)$$

restricts the emission density for current sources to be greater or equal to e^{base}, their current value adjusted to show compliance with applicable regulations. This base or floor for current sources must be respecified at a lower yet still feasible value.

It is unlikely that one would set the minimum emission levels for current sources as low as those of future sources. With older plant and equipment, current sources would find it more difficult to meet such standards as new development. Also, the options of locating on a site with a higher emission density or purchasing additional land are not as easily available to the current emission source as they are to a future source.

Within the range between the current emission density and the lower limit that is used for future sources, one must specify a lower bound. The most straightforward way of doing this is to:

a. Catalogue the possible emission reductions for each current source category. This would basically be various types of control equipment, process modification or fuel switching.

b. Convert the maximum emission reduction to a minimum emission density. This would have to be done separately for each component area and point source, as densities of development will differ.

c. Use this value as the e^{base} parameter of equation (36).

This method has two shortcomings. The first is that the cost of control is not considered if the emissions maximisation formulation of the model is utilized. The second is that it is assumed that emissions can be abated to any point down to the minimum level. Neither shortcoming is particularly serious, the former can be resolved by using the control cost formulation of the model, the latter is not serious since most sources will have emission density limits set at their lower or upper bounds.

However, combining the attainment and maintenance problems into one model sidesteps the issue of how much emissions growth will be permitted at new sources and, concurrently, how much emissions reduction will be required at existing sources. If it is not the intent or policy to treat the two classes of sources identically, it is more satisfactory to separate the two problems and treat the trade-off between growth and current sources openly.